In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institute shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, or, in his absence, by the Dean of the Graduate Division when such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

7/25/68

EFFECT OF ANNEALING ON ALUMINUM ALLOYS FOR ELECTRICAL CONDUCTORS CONTAINING IRON, COBALT, NICKEL AND MAGNESIUM

A THESIS

Presented to

The Faculty of Graduate Division

by

Nirmal Kumar Datta

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Metallurgy

Georgia Institute of Technology

June 1971

EFFECT OF ANNEALING ON ALUMINUM ALLOYS FOR ELECTRICAL CONDUCTORS CONTAINING IRON, COBALT, NICKEL AND MAGNESIUM

Approved:

Chairman

Date approved by Chairman: May 25-71

ACKNOWLEDGMENT

The author is deeply indebted to his thesis advisor, Dr. Niels N. Engel, for his inspiring guidance, many helpful suggestions, sustained encouragement and stimulating discussions.

It gives the author great pleasure to thank Drs. Edgar A. Starke, Jr., and Stephen Spooner for having taken time to review this work. Their interest and constructive criticism is highly appreciated.

The author sincerely thanks Dr. W. R. Clough and Mr. Henry Chia for providing experimental assistance in this work and their timely help on many occasions.

The financial support of this research provided by Southwire Company, Carrollton, Georgia is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Concluded)

LIST OF FIGURES

LIST OF FIGURES (Continued)

SUMMARY

The main object of the present investigation was to study the properties of newly developed conductor grade aluminum alloys which have higher mechanical strength than conductor grade aluminum and sufficient conductivity to make them economically competitive with copper. The properties of these alloys are based on a dispersioned hardened matrix in which the alloying element is practically insoluble at room temperature. The lack of solubility ensures a conductivity approaching that of pure aluminum.

In the present work binary, ternary and quarternary alloys of aluminum were prepared with different amounts of iron, cobalt, nickel and magnesium. Cold drawn wires of different diameters were heat treated in the temperature range between 300°F and 1000°F and the electrical conductivity and mechanical properties were measured at room temperature.

The results of the present investigation show that a superior product can be obtained from Al-Fe-Co-Mg alloy which is better than binary and ternary aluminum alloys. This alloy appears to be a promising conductor material which can replace copper in several industrial applications.

CHAPTER I

INTRODUCTION

Though mining specialists insist that there is enough of copper to meet the world's demand for foreseeable future, both supply and cost become unstable periodically. Strikes, control of export for price control by foreign governments, and occasional political turmoil contribute to an uncertain copper market. In this situation, engineers turn to the next best but cheaper conductor material, aluminum.

In recent years, the aluminum conductor cables (1, 2) have virtually eliminated the use of other materials for transmission and distribution because they offer the desired properties at the lowest cost. The electrical use (3) of aluminum conductors accounted for 715,000,000 pounds in the U.S.A. in 1969. Electrical conductor grade (EC) aluminum is used for insulated conductors, non-metallic sheathed cable, communications cable, magnet wire, and appliance wiring. The amount of aluminum utilized in these applications is gradually increasing because aluminum offers advantages in cost and weight over copper. Furthermore, the favorable conductivity to weight ratio of aluminum makes it better suited for such applications as those in aerospace industries.

Complete utilization of aluminum for industrial purpose is limited by its low mechanical strength, bendability and connection stability. Improvement of all these properties, therefore, will make aluminum an excellent conductor material for a wide variety of applications.

There has been considerable research (4, 5, 6, 7, 8) on the development of high strength aluminum wire for electrical applications. The results showed that the addition of small amounts of alloying element improve the strength properties without much deleterious effect on electrical conductivity. In the present investigation, an attempt has been made to develop conductor grade aluminum alloys by addition of small amounts of alloying elements which exhibit low solid solubility at room temperature and form stable compounds which might act as strengthening agents. To be effective, these precipitates (8) should be less than one micron and homogeneously distributed throughout the matrix. Iron, cobalt and nickel appeared to be attractive, since they form stable intermetallic compounds (9) Al_3Fe, Co_2Al_9 and Al_3Ni. Magnesium was also added to some of these alloys as an additional alloying element in an attempt to enhance the strength properties. In order to investigate the difference in properties of these alloys, the influence of annealing temperature and time was also studied.

CHAPTER II

LITERATURE REVIEW

Dispersion Strengthening

Dispersion strengthening is one of the most important techniques of the developing of high strength aluminum alloys. In the present application, the design of a high strength conductor grade aluminum alloy should be such that the alloying elements have little solubility at room temperature and form stable precipitates which act as a strengthening agent. These stable precipitates are broken up during rolling and drawing operations and uniformly distributed throughout the matrix. The dispersions of the precipitates have a powerful influence on the electrical conductivity and mechanical properties such as tensile strength, yield strength, fatigue behavior and creep resistance.

Variables including casting method, the ratio of different alloying elements, homogenizing treatment, thermal cycle and intermediate anneal have a strong influence on the dispersion rate, and hence on recrystallization and mechanical properties. The work of Scharf and Gruhl (10) showed that the grain boundary movement during recrystallization is mainly influenced by the radius, r, of the precipitates and their volume fraction, f, in the following relationship which is called the "dispersion rate"

$$V_d = \frac{f}{r}$$

According to these authors, coarse precipitates, which result from homogenization, accelerate grain growth, whereas fine precipitates generated during hot rolling, lead to a marked decrease in grain growth. Since only these subgrains of sufficiently large size are active for recrystallization, the retarding of recrystallization by fine precipitates can be explained mainly by inhibition of nucleation.

The finer precipitates together with smaller cell size enhance the mechanical strength of aluminum alloys. The obvious reason (8) is that the cell wall and the precipitate particles act as barriers to the movement of dislocations and thereby improve the strength properties.

Effect of Alloying Elements on the Electrical Conductivity and Mechanical Properties of Aluminum Alloys

The electrical conductivity of aluminum is sensitive to composition, heat treatment, degree of deformation and temperature. All known (9) additions to aluminum reduce its electrical conductivity. Metals in solid solution depress the conductivity to a greater extent than when out of solution. The effect of two or more additions on the resistivity of aluminum depends on the relation between the elements. In general, if the elements individually go into solid solution in aluminum, their effects on resistivity are additive. If a compound is formed, the solid solubility of one or both elements may be reduced.

The mechanical strength of aluminum alloys in annealed condition will depend essentially on the dispersion rate of the precipitate particles. It is, however, believed (11) that the dispersion strengthening with compounds of transition elements which contribute to d electron bonds may enhance the strength properties. The transition elements iron, cobalt and nickel are the least expensive and easiest to handle materials. The refractory metals would require inert gas or vacuum melting and the elements in the middle of the transition period would exhibit so a high melting point that they are difficult to put into solution. The present investigation, therefore, concentrated on iron, cobalt and nickel alloys. Past work (7) by several investigators showed that magnesium has a beneficial effect on mechanical properties. Therefore, the influence of small amount of magnesium was included in the present study. The influence of these elements on the properties of Al is summarized below:

1. Iron: Iron increases the resistivity (9) 2.56 μohm-cm/wt% of Fe in solution and 0.058 μohm-cm/wt% of Fe out of solution. Small additions of Fe increase the tensile strength of Al with no deleterious effects on elongation and conductivity. With increase in Fe concentration the hardness increases in the cold drawn wire and decreases slightly in annealed wire.

2. Cobalt: Cobalt reduces the electrical conductivity of aluminum. With a 0.26% increase in Co, the specific resistance of aluminum increases by about 0.09 microhm-cm for an annealed wire (12). With increasing concentrations of Co the strength of the cold-drawn and annealed wire increases while the specific elongation decreases. The positive effect of cobalt on the mechanical properties of aluminum may be due to the formation of the high melting, hard phase Co_2Al_9, which by exerting a modifying influence, refines (12) the structure and

strengthens it.

3. Nickel: With increase in nickel concentrations from 0.52 to 1.05 wt% the strength of the annealed wire increases (12) from 12.63×10^3 to 13.76×10^3 psi and the specific resistance increases from 2.68 μohm-cm to 2.76 μohm-cm. The specific elongation of the cold-drawn and annealed wire is higher for the alloys with nickel than for the alloys with iron.

4. Magnesium: Magnesium exerts a considerable effect on the conductivity of super purity Al. The results of Gauthier's (14) experiment showed that the resistivity increases by 0.026 μohm-cm for each 0.05% Mg present in the alloy. When some impurity like Si is present in the alloy, the effect may be very different on the account of the formation of the compound Mg_2Si. Within the region of solid solubility, the effect of Mg_2Si is practically the same as that of Mg. It appears from the work of Gauthier (14) that the maximum solubility limit of Mg_2Si is less than 0.14%. The Mg_2Si concentration of 2.5% increases the electrical resistivity of 99.92% Al from 1.712 μohm to 2.528 μohm when present out of solution.

Magnesium also changes the mechanical properties (9) of Al alloys. The tensile and yield strengths increase continuously as the concentration of Mg is increased to 10 percent or higher, whereas the elongation passes through a minimum of about 27 percent at 2 to 3 percent Mg.

CHAPTER III

EXPERIMENTAL PROCEDURE

Fabrication of Aluminum Wire

The aluminum wire used in the present investigation were produced both by laboratory procedures of melting and casting and by the Southwire Continuous Rod (SCR) System (13, 15) at Carrollton, Georgia. The plant produced ingots were melted and alloyed in a reverberatory furnace and cast into billet by their continuous casting machine. This was followed by immediate continuous hot rolling the billet to 3/8 inch diameter rod which was air cooled from 350°F in 5 ton coils. The untreated rod was drawn to wires of different diameters ranging from 3.20 mm to 1.63 mm. The laboratory batches were melted in the high frequency furnace using a graphite crucible and cast into one inch diameter rod in a cast iron mold. The ingots were reheated to 950°F and hot rolled to 3/8 inch diameter rods. The rods were cold drawn to wires of various diameters as mentioned above. Wires were tested in both the cold drawn as well as in a series of heat treated condition. Analyses of the alloy wires used in the present investigation were made in the metallurgical laboratory of Southwire Company using a Baird Atomic Direct Reader spectrograph analyzer. The results are given in Table 1.

Heat Treatment of Wire

The hard drawn wires were annealed at different temperatures, ranging from 300°F to 1000°F for three hours in order to investigate the

Table 1. Composition of Different Aluminum Alloy Wires in Weight Percentage

1.	Al-0.6% Fe
2.	Al-0.8% Ni
3.(a)	Al-0.2% Co, (b) Al-0.6% Co (c) Al-0.8% Co (d) Al-1.0% Co
(e)	Al-1.2% Co.
4.(a)	Al-0.8% Co-0.05% Mg (b) Al-0.8% Co-0.1% Mg (c) Al-0.8%-0.2% Mg
5.(a)	Al-0.78% Fe-0.82% Co-0.006% Mg
(b)	Al-0.69% Fe-0.40% Co-0.08% Mg
(c)	Al-0.63% Fe-0.49% Co-0.028% Mg
(d)	Al-0.52% Fe-0.49% Co-0.024% Mg
(e)	Al-0.88% Fe-0.58% Co-0.0017% Mg
(f)	Al-0.74% Fe-0.60% Co-0.0024% Mg

influence of the annealing temperature. The influence of annealing time was also tested by varying the annealing time from 1 to 7 hours at some selected temperatures mostly 400°F, 500°F and 600°F. The wire specimens were heated in a Lindberg-Heavy Duty furnace equipped with a horizontal quartz tube one inch diameter. The specimens were placed into the furnace which was preheated to the required temperature of heat treatment. Each time a platinum-platinum 10 percent rhodium thermocouple was inserted into the furnace so as to check the temperature shown by the furnace recorder. The variation in temperature with time as recorded by the thermocouple was within the range ± 5°F for all temperatures. The specimens were taken out of the furnace after the specified time of heat treatment and allowed to cool in air. To assure uniform heat treatment of the wires the temperature profile of the furnace was checked by thermocouple readings at one inch distances over the used 10 inches length. All temperature readings were within ± 2.5°C from average.

Determination of Electrical Conductivity

The conductivity of both hard drawn and heat treated wires were determined by measuring the electrical resistivity of wires in a 1600-1610 Honeywell Kelvin Bridge which is sensitive to one millionth of an ohm. The resistivity values were then converted to conductivity and compared with the International Annealed Copper Standard, IACS. If R' is the specific resistance of an annealed copper at room temperature and R'' is the specific resistance of the aluminum alloy at the same temperature, then the percentage IACS = $\frac{R'}{R''} .100$.

Mechanical Testing

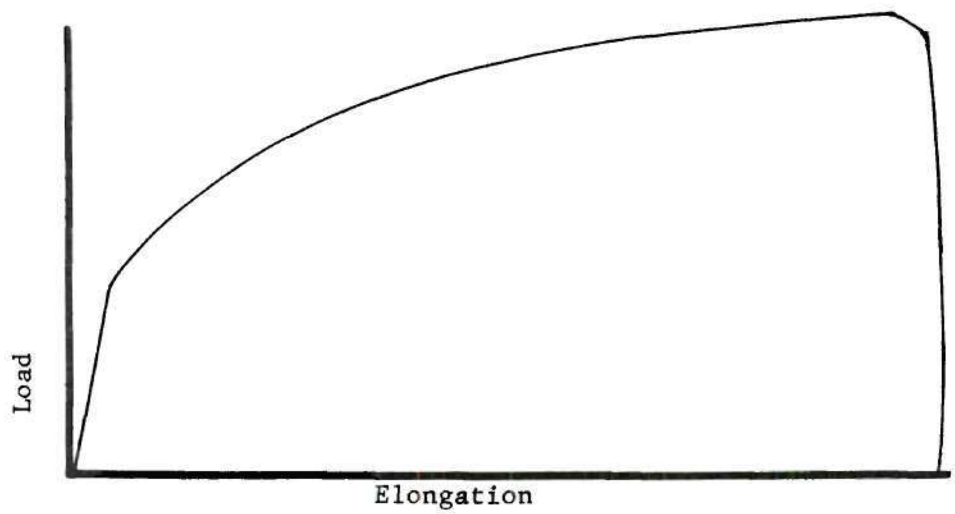
Ultimate tensile strength, yield strength and percentage elongation were measured using an Instron tensile testing machine at a strain rate of 0.5 inch per minute. The load-elongation curves were recorded on the chart using a speed of 5 inches per minute. The percentage elongation was determined by measuring the distance between the tape marks, spaced 20 cm apart in the gauge length section of the wire, before and after pulling in the machine. The cold drawn wire and some of the Al-alloy wires heat treated below 450°F showed jaw fracture whereas wires heat treated to the temperatures between 500°F and 1000°F showed fracture within the gauge length section of the wire. Figure 1 shows typical load-elongation curves of an annealed copper and some of the Al-alloy wires used in the present work.

Metallography

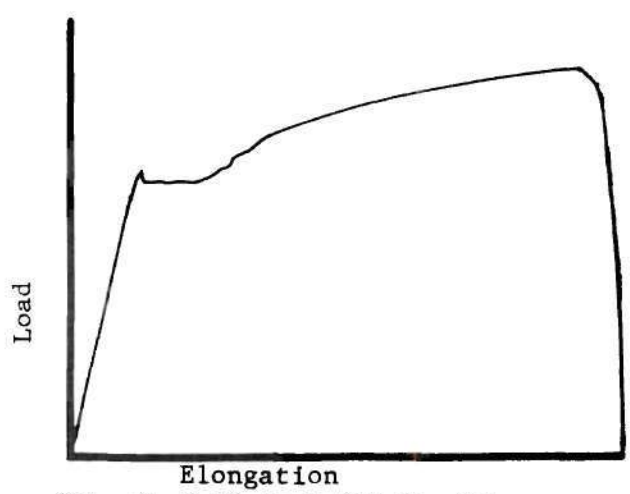
Different specimens of one Al-Fe alloy and several Al-Co, Al-Co-Mg and Al-Co-Fe-Mg alloys were prepared for metallographic studies and photomicrographs taken. Metallographic examinations were made on both the cast sample (slow and fast cooled) and hot rolled 3/8 inch diameter rod. In case of rod, cross-sections of the specimens were examined. All the samples were electropolished with a solution containing 70 percent ethanol, 10 percent butoxyethanol, 8 percent perchloric acid and 12 percent water.

X-Ray Diffraction

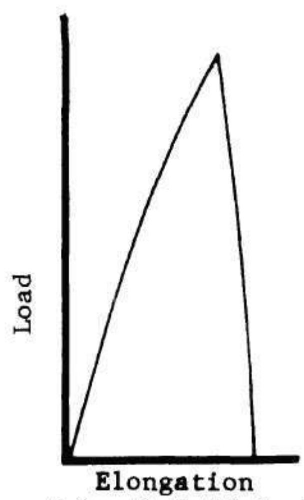
X-ray analyses were made on some of the Al-Co alloys and Al-Fe alloys using a General Electric XRD-6 diffractometer equipped with a Warren doublybent monochromator.



(a) Annealed Copper



(b) Al-0.8% Co-0.05% Mg Alloy
Annealed at 450°F.



(c) Al-0.8% Co-0.05% Mg
Alloy Hard Drawn.

Figure 1. Schematic Load-Elongation Diagram.

CHAPTER IV

DISCUSSION OF RESULTS

Metallography

The laboratory chill cast samples of Al-0.6% Fe, Al-0.8% Ni and Al-0.5% Fe-0.4% Co-0.05% Mg alloys were examined in the optical microscope. The microstructures, Figures 2a, 2b and 2c, revealed a network of eutectic precipitates at the dendrite boundaries. These precipitates are intermetallic compounds formed by the alloying elements which are added to aluminum. In case of Al-Fe and Al-Ni binary alloys, the intermetallic compounds (16, 17) are Al_3Fe and Al_3Ni and for the Al-0.5% Fe-0.4% Co-0.05% Mg alloy, a compound with the Co_2Al_9 structure is present in largest amounts, as identified by X-ray analysis.

The intermetallic compound precipitates were broken up and dispersed during the rolling and drawing operation and enhanced the strength properties. Furthermore, Figures 3a and 3b show that addition of Mg to Al-Co alloy produces pseudo-eutectic in the slow cooled condition and these finer precipitates, which can not otherwise be seen in chill cast alloy, increased the mechanical strength. It can also be seen from Figures 2a, 2b and 2c that Al-0.5% Fe-0.4% Co-0.04% Mg alloy has smaller dendrite spacing as Al-0.8% Ni and Al-0.6% Fe alloys. The superior strength properties of Al-0.5% Fe-0.4% Co-0.05% Mg alloy are related to the dendrite spacing in an expected manner.

It is clear from these results that, with adequate processing

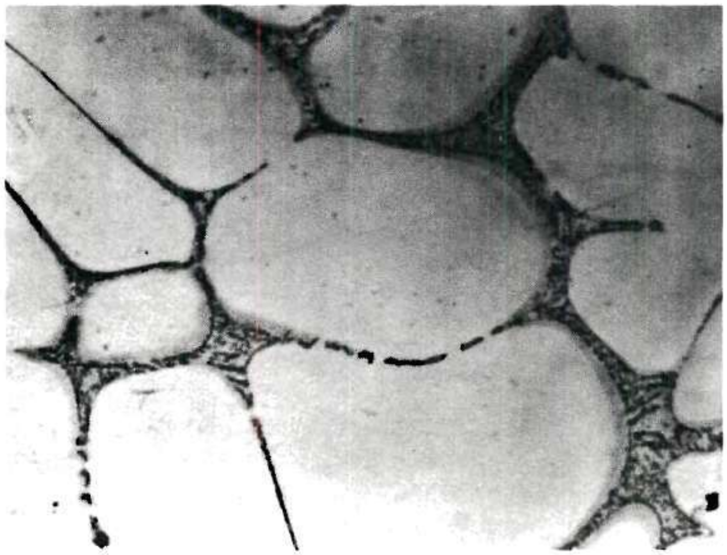


Figure 2a. Chill Cast-Al-0.6% Fe. Primary Crystals of Al Surrounded by a Network of Eutectic Al+Al_3Fe, Only Partially Resolved by the Enlargement Used, X 400 Electropolished.

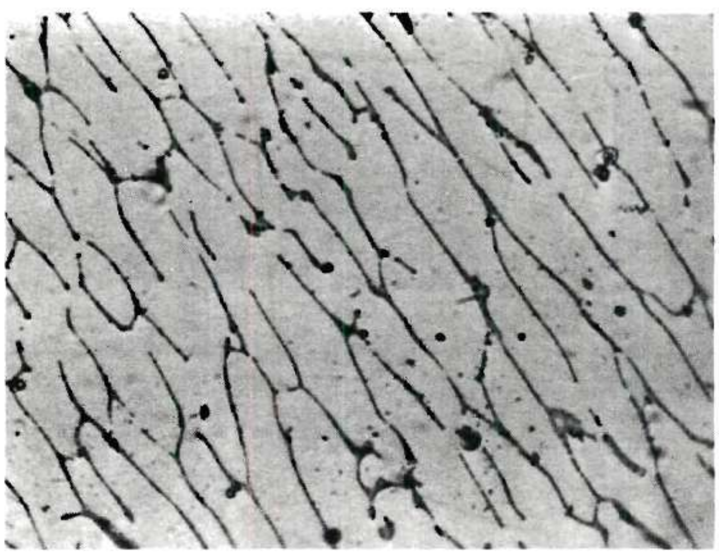


Figure 2b. Chill Cast-Al-0.8% Ni. Primary Crystals of Al Oriented in the Direction Barallel to the Heat Flow and a Network of Degenerated Eutectic Al+Al_3Ni, X 400 Electropolished.

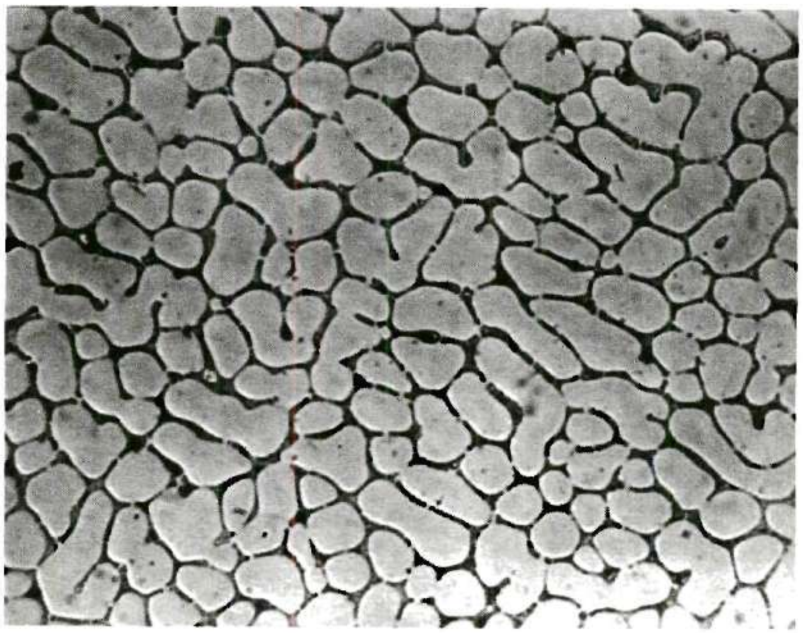


Figure 2c. Chill Cast-Al.4% Co-0.5% Fe-0.056% Mg. Dendrites of Primary Al Crystals with a Network of Eutectic, X 400, Electropolished.

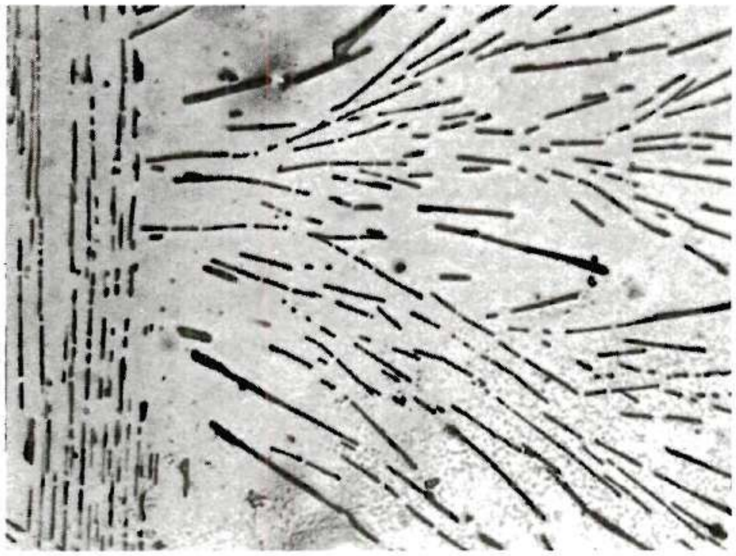


Figure 3a. Slow Cooled-Al-1.0% Co. Long Needles in the Al Solid Solution Matrix. Entire Structure is Eutectic, X 200, Electropolished.

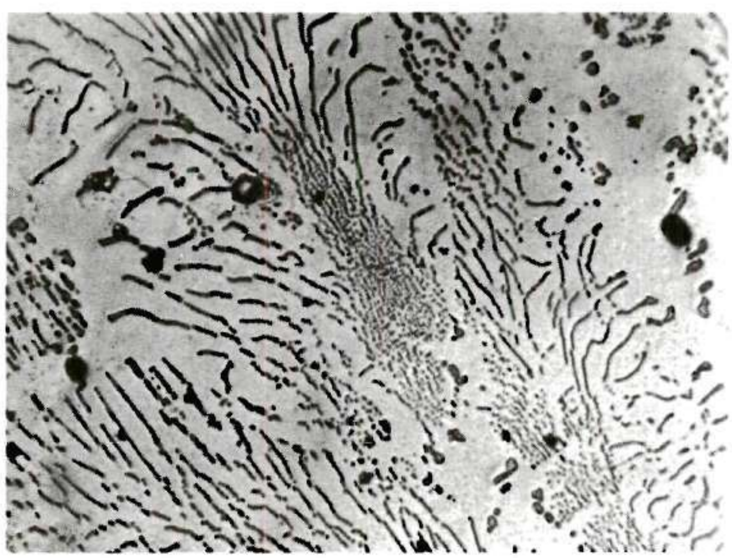


Figure 3b. Slow Cooled-Al-0.7% Co-0.21% Mg. Essentially Eutectic Structure in which the Compound Platelets are Shortened and Partly Broken up. Patches of Fine Eutectic also Visible With Broken up Compound Lamellae, X 200, Electropolished.

control, alloys of very high strength can be produced from direct chill ingot. The rapid solidification rate, and hence the finer dendrite arm spacing (18) obtained from the direct chill ingot, permits smaller cell structure to be obtained in the final product.

The Electrical Conductivity and Mechanical Properties of Aluminum Alloys

A brief review of the present results show that alloying elements like iron, cobalt, nickel and magnesium improve the mechanical strength of conductor grade aluminum without much deleterious effect on electrical conductivity. The mechanical properties and electrical conductivity depend to a great extent on the type and amount of alloying element and whether the alloying elements are added separately or together. Iron, cobalt or nickel when added separately improves the mechanical strength of conductor grade aluminum with minimum loss of conductivity.

Figure 4 compares the conductivity and elongation with varying yield strength of conductor grade aluminum and the newly developed aluminum alloys. Al-0.8% Ni alloy exhibits the best combination of yield strength, and elongation and conductivity of all the binary alloys. In case of ternary and quarternary alloys, the Al-0.78% Fe-0.82% Co-0.006% Mg alloy was found to have mechanical properties superior to any of the binary alloys but its conductivity is slightly inferior.

Both binary and complex alloys show conductivity maxima which correspond to the recrystallization temperature of the alloys. The maximum conductivity is partly due to the recrystallization of the cold worked material and partly due to the precipitation of the alloying

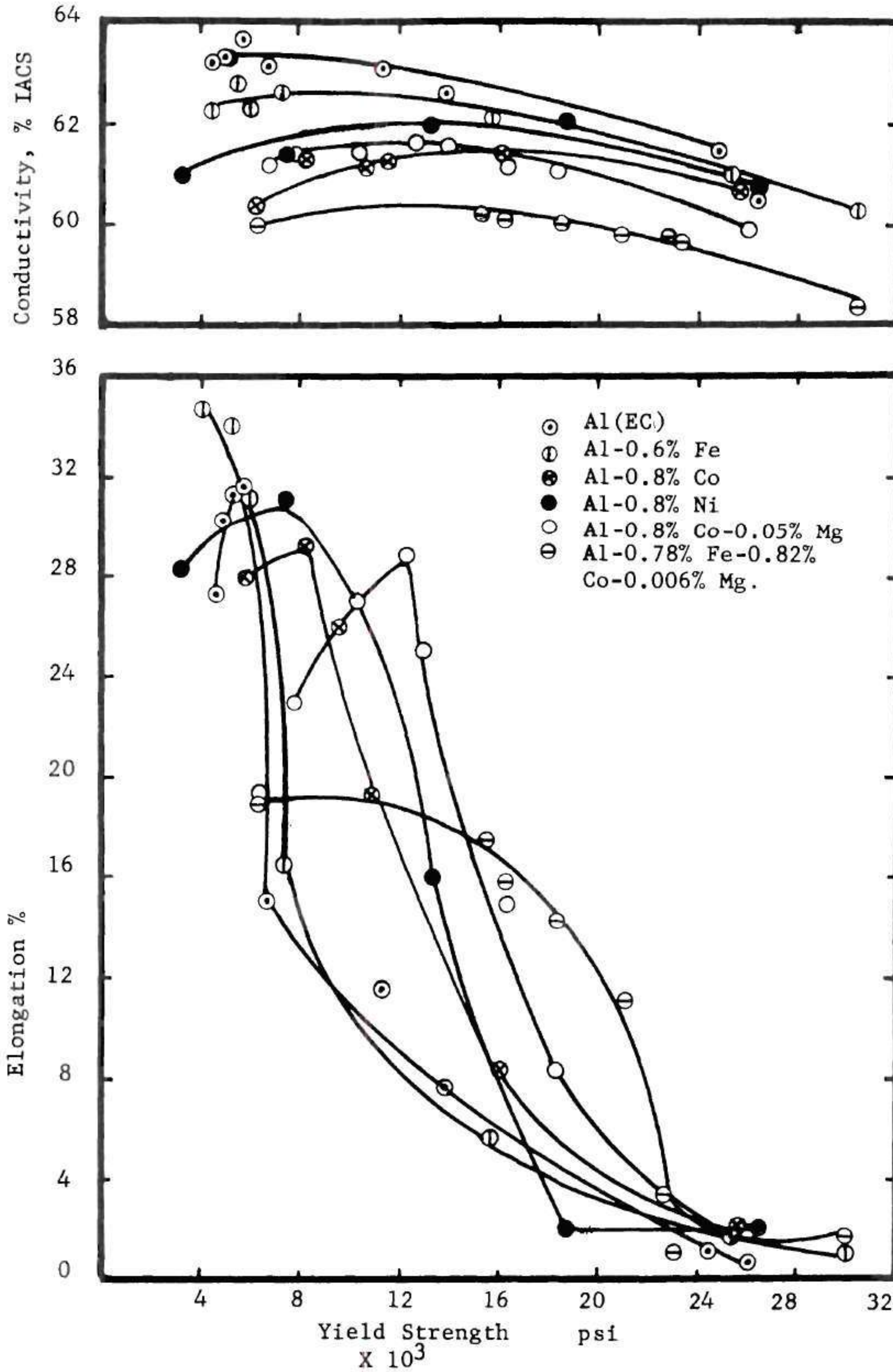


Figure 4. Comparison of Conductivity and Elongation with Yield Strength of Different Aluminum Alloys.

element from the solid solution. The elongation curves also show maxima which correspond to the complete recrystallization of the cold worked material before grain growth takes place. The increased strength of the alloys is attributed to the interaction of the dislocations with the intermetallic precipitates and subgrain boundaries.

Since Al-0.8% Ni alloy appears to be the most attractive of all the binary alloys, the behavior of this alloy with annealing temperature and time is very important. Figures 5, 6 and 7 show the change in mechanical properties and conductivity with annealing temperature and time. It is evident from the above mentioned figures that the tensile strength and yield strength are lowered with increasing temperature and time of annealing, however, the conductivity and elongation are improved until at higher temperature where this effect is reversed. It can also be seen from Figure 7 that at 600°F the elongation reaches a maximum during the first hour of anneal and then drops with increasing time. At lower temperature around 400°F to 500°F, however, the elongation increases with increasing time of annealing. One possible explanation is that the recrystallization of Al-0.8% Ni alloy takes place at a temperature around 350°F and the drop in elongation at higher temperature is due to grain growth. The conductivity is improved from 60.85% IACS to 62% IACS by annealing at 350°F due to recrystallization and precipitation of Ni from solid solution.

The variations of conductivity and strength properties with temperature and time of Al-Fe-Co-Mg alloys were also studied and the Figures 8, 9 and 10 illustrate the typical behavior of Al-0.88% Fe-0.58% Co-0.0017% Mg alloy. It can be seen from the figures that annealing improves

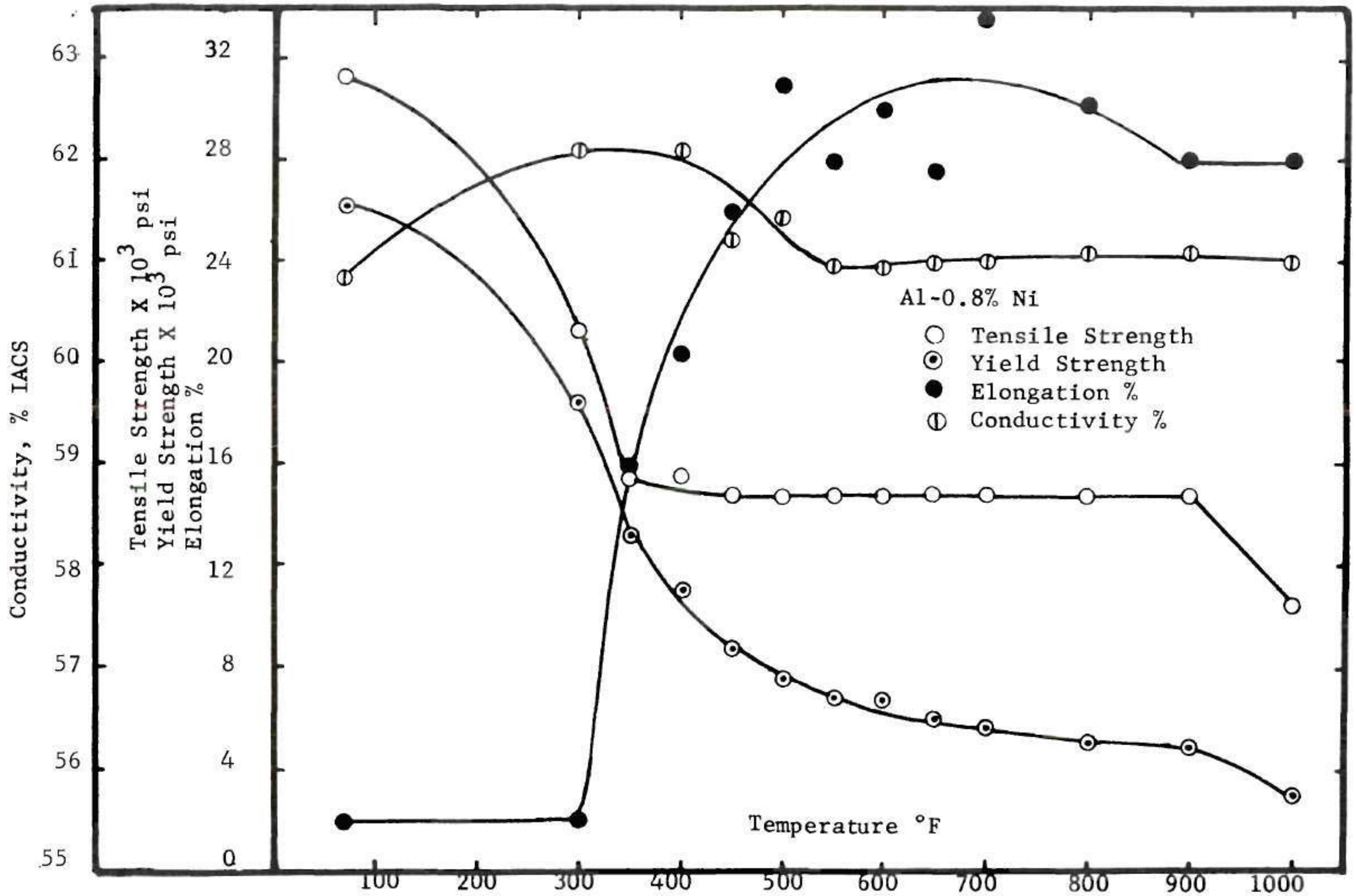


Figure 5. Al-0.8% Ni Alloy. Variation of Electrical Conductivity and Mechanical Properties with Temperature for Three Hours Anneal.

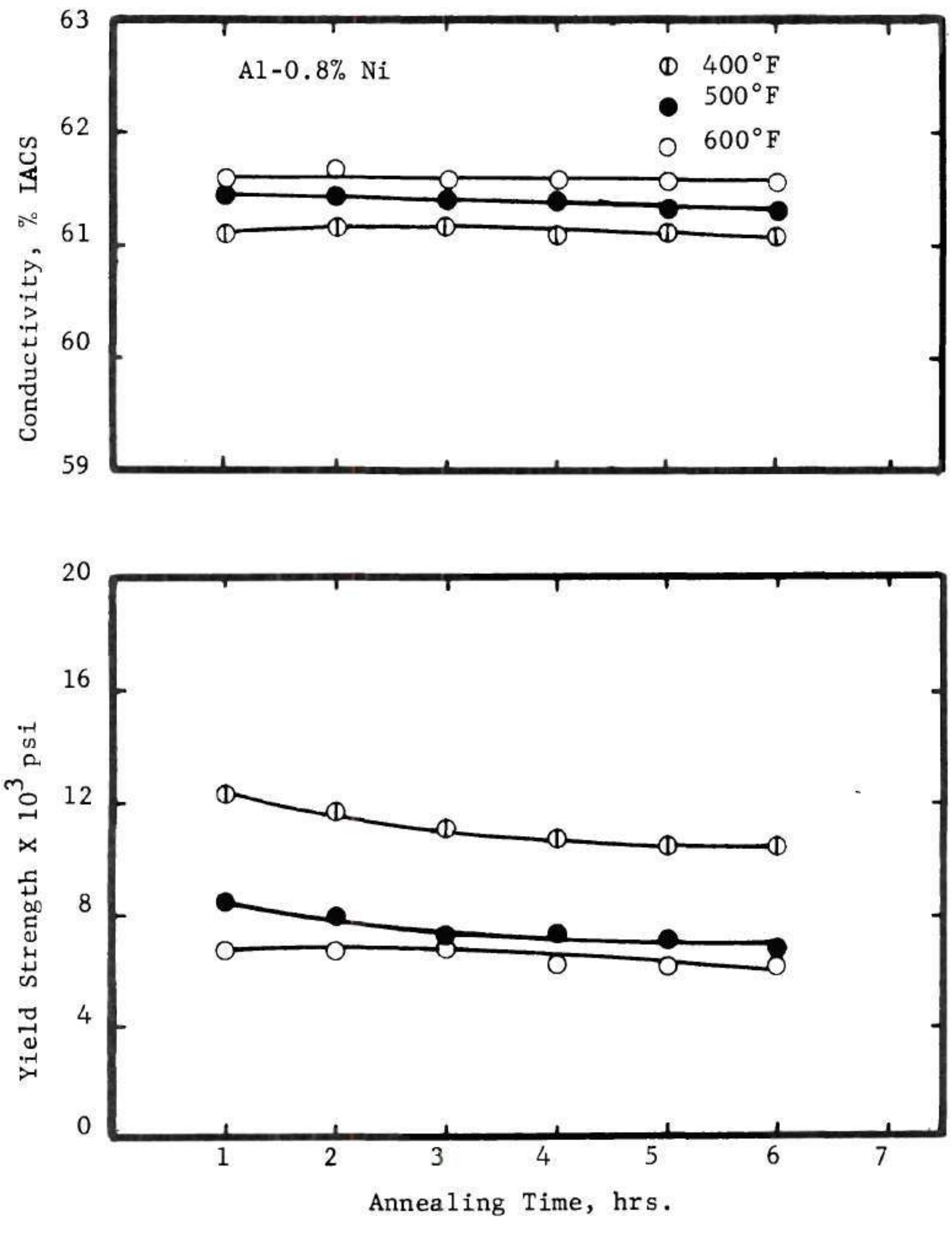


Figure 6. Al-0.8% Ni Alloy. Variation of Electrical Conductivity and Yield Strength with Annealing Time.

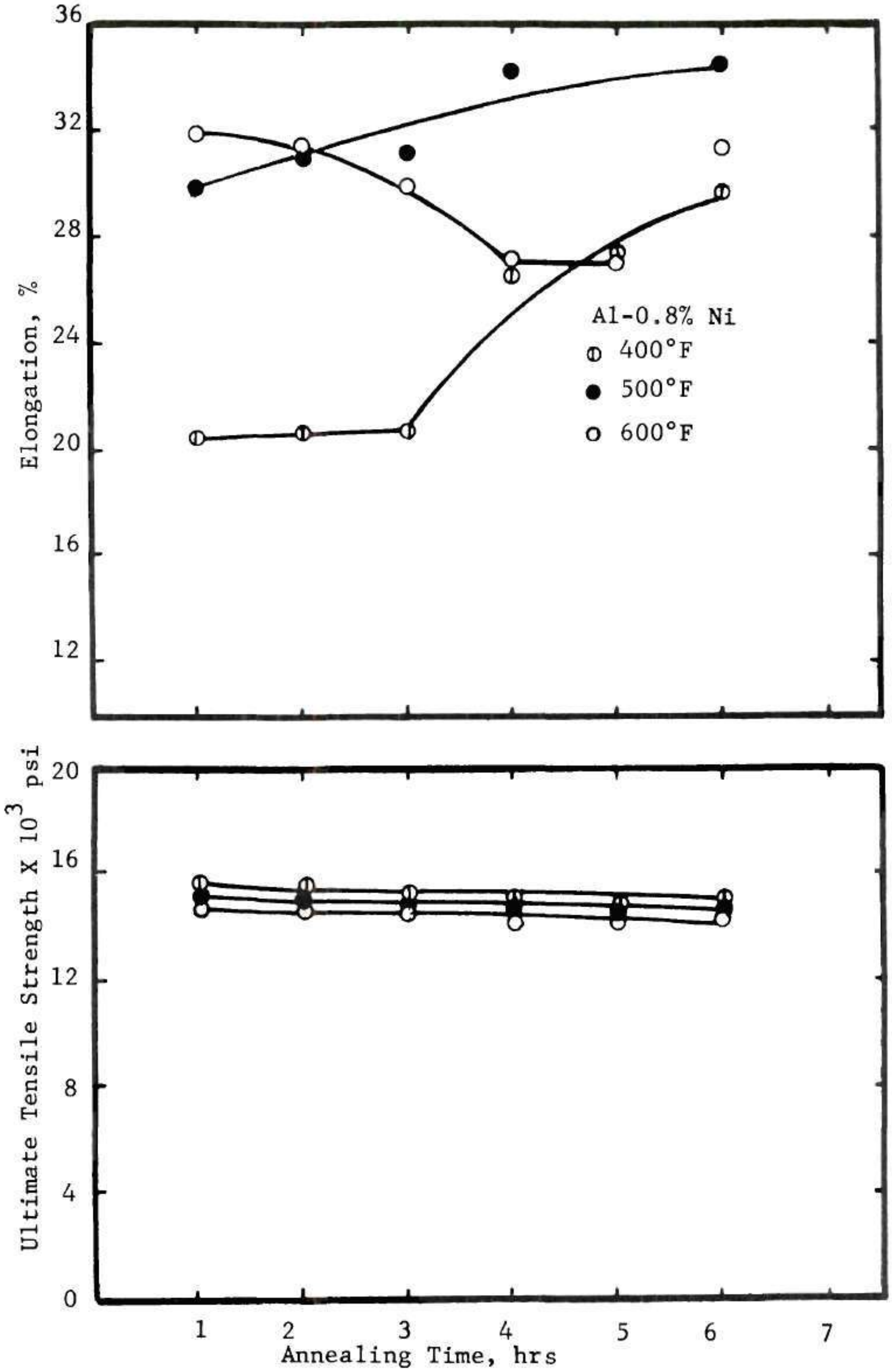


Figure 7. Al-0.8% Ni Alloy. Variation of Elongation and Ultimate Tensile Strength With Annealing Time.

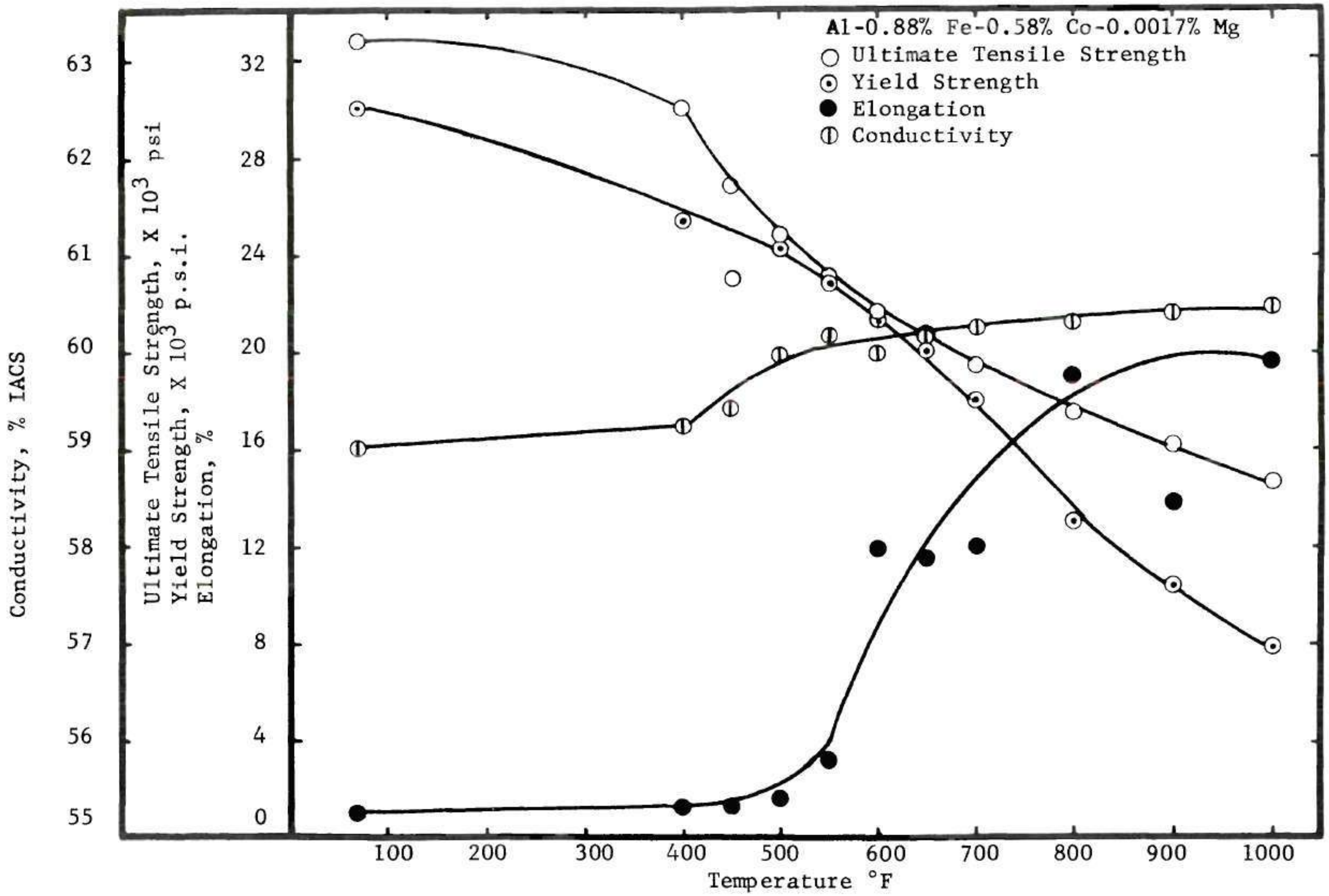


Figure 8. Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy. Variation of Electrical Conductivity and Mechanical Properties with Temperature for Three Hours Anneal.

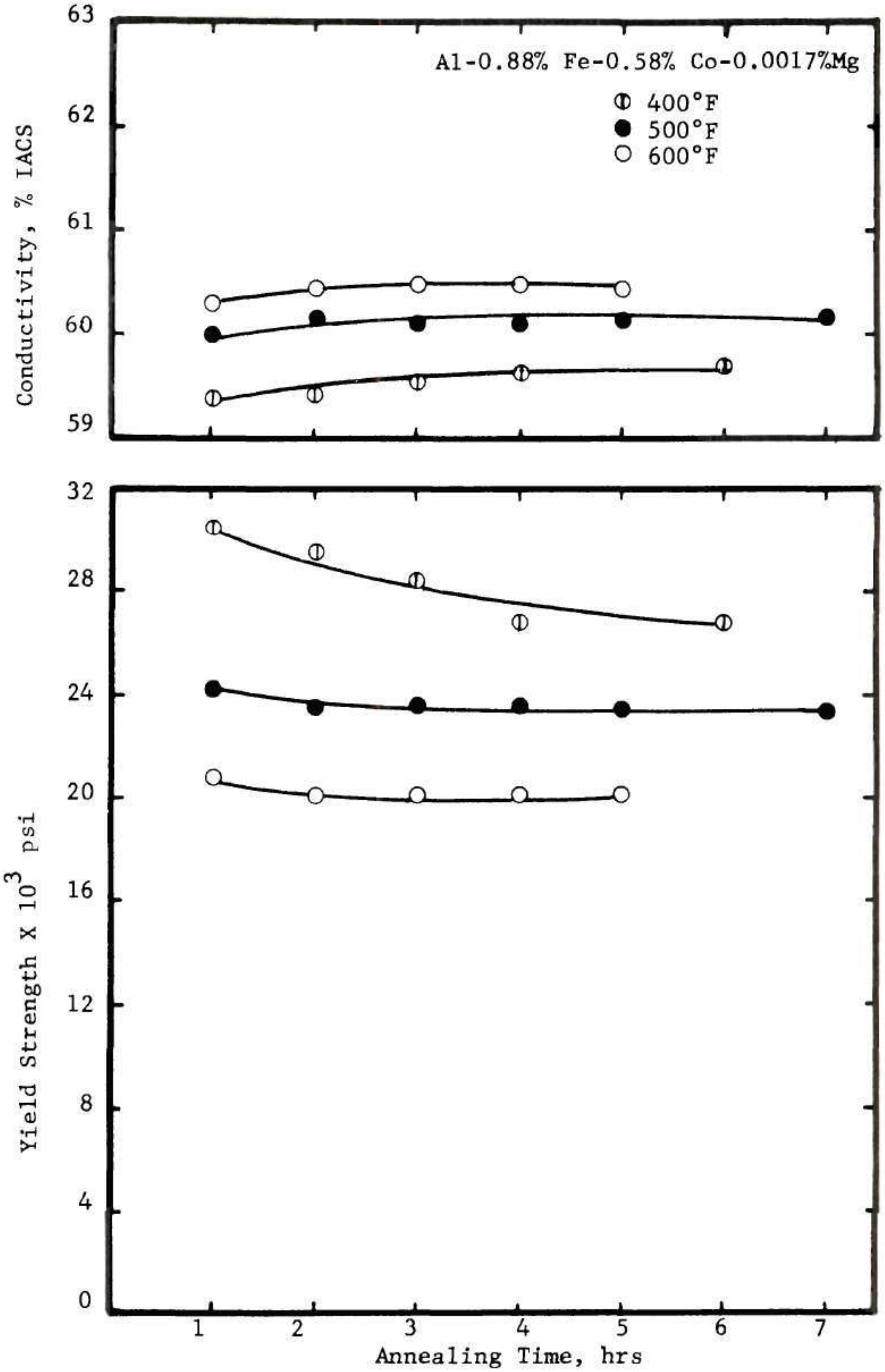


Figure 9. Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy. Variation of Electrical Conductivity and Yield Strength with Annealing Time.

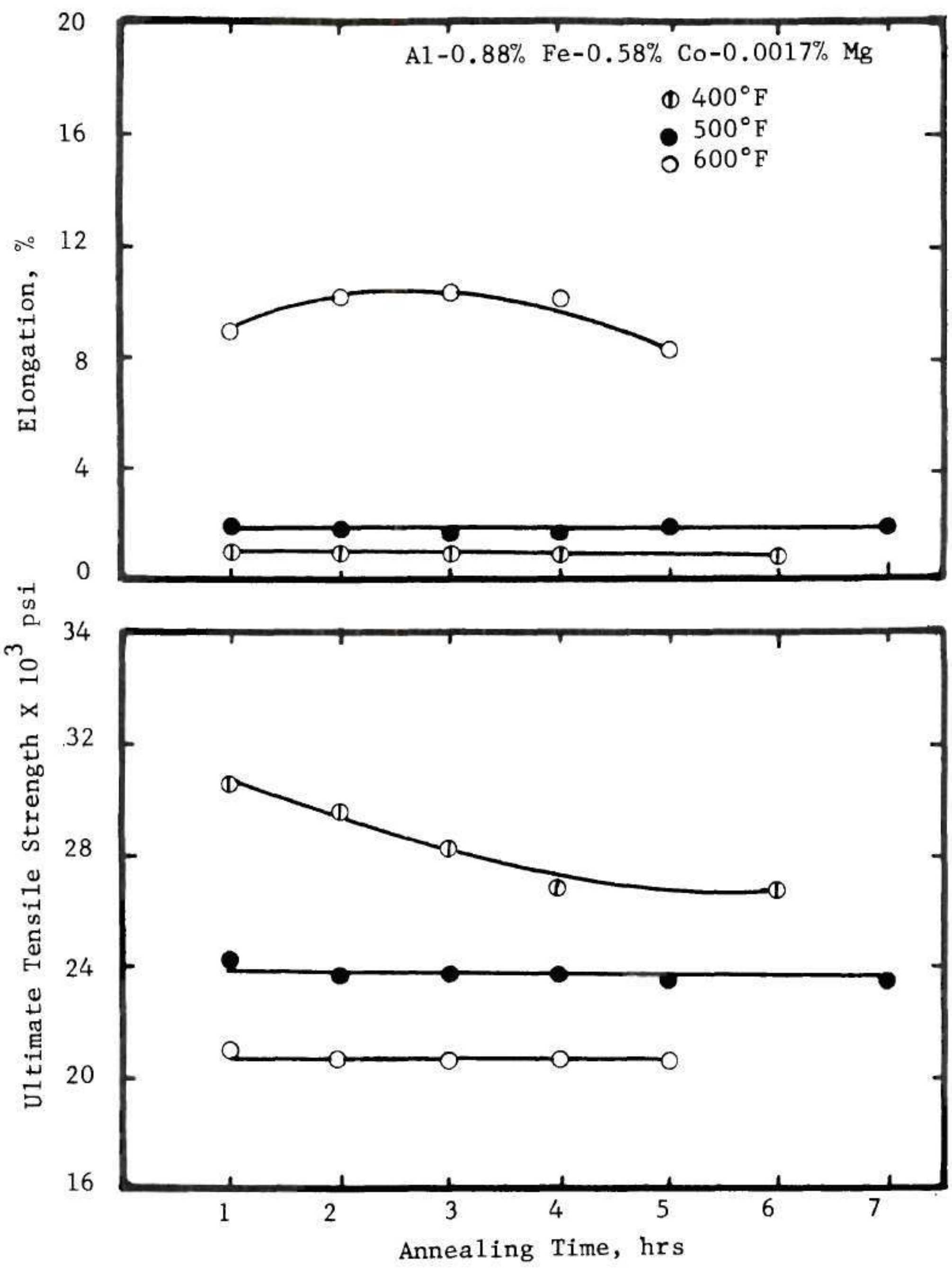


Figure 10. Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy. Variation of Elongation and Ultimate Tensile Strength with Annealing Time.

conductivity at the sacrifice of strength. The increase of conductivity and lowering of strength properties are mainly due to recrystallization of cold worked material and the conglomeration of precipitates at higher temperature of annealing.

The influence of time on conductivity and mechanical properties of Al-Fe-Co-Mg alloys was studied at 400°F, 500°F and 600°F and results are shown in Figures 9 and 10. The strength properties are reasonably good at lower temperature around 400°F to 500°F but the elongation is very poor and does not improve with time. At higher annealing temperature around 600°F, the conductivity and elongation are improved at the expense of a large drop in mechanical strength. It can also be noted from Figure 10, that the elongation first increases with time, reaches a maximum at three hours and then decreases again at 600°F. The decrease in elongation with longer annealing time is due to grain growth.

Since Al-Fe-Co-Mg alloys exhibit the superior mechanical properties, the influence of Fe, Co and Mg on these properties were studied in detail. Figures 11 and 12 illustrate the effect of varying amount of cobalt on conductivity, yield strength and tensile strength of conductor grade aluminum. It is clear from these figures that higher percentages of cobalt improve the strength properties at the cost of conductivity in cold drawn as well as in annealed conditions. It can also be seen from Figures 13 and 14 that addition of Mg to Al-0.8% Co alloy impairs the conductivity but improves the mechanical strength. At higher temperature of annealing, the improvement of strength is not so prominent as at lower temperature. The combined effect of Fe and Co is illustrated in Figure 15 and it is evident that the yield strength

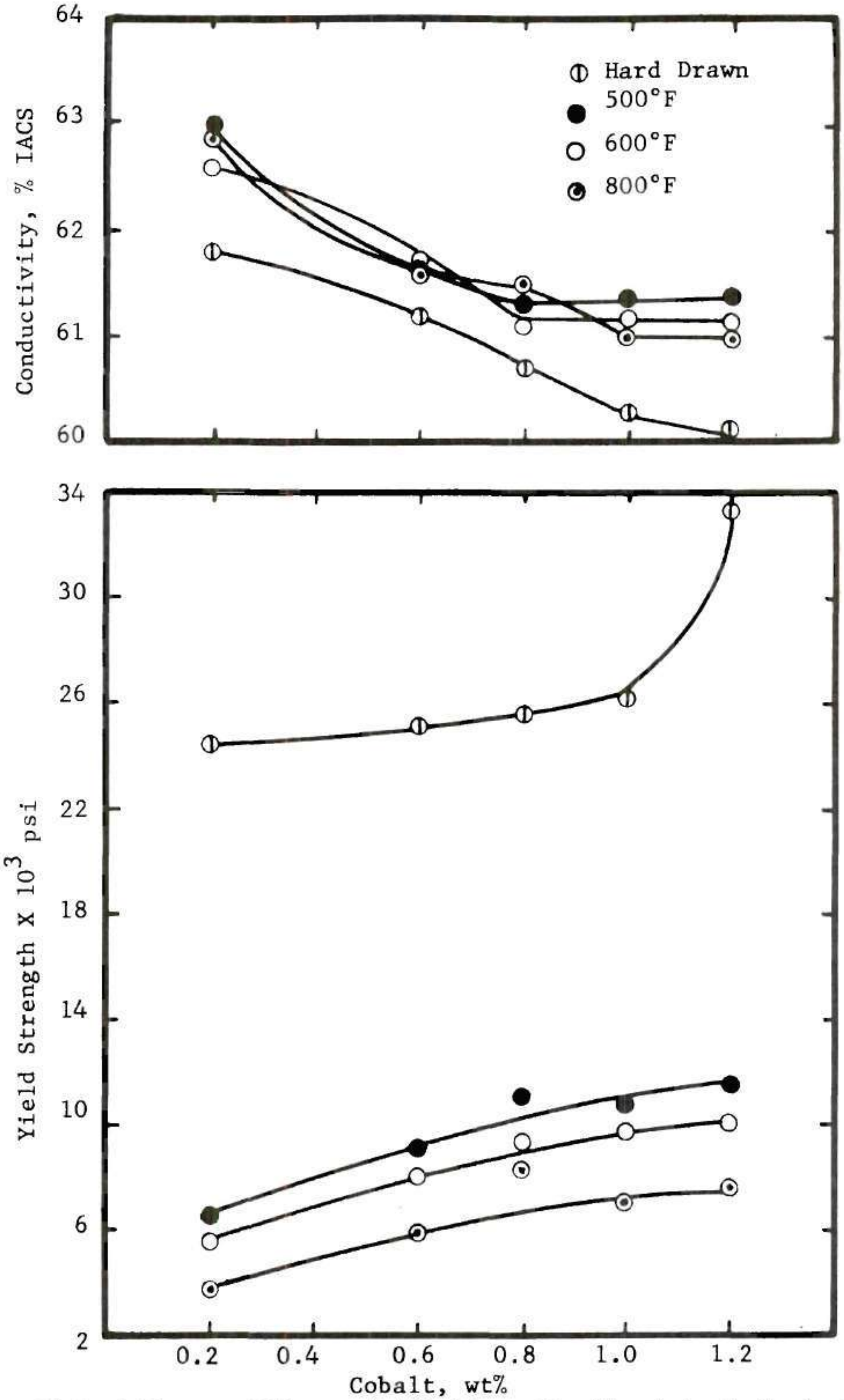


Figure 11. Al-Co Alloys. Effect of Cobalt on the Electrical Conductivity and Yield Strength of Aluminum in Hard Drawn and Annealed (500°F, 600°F, 800°F) Conditions.

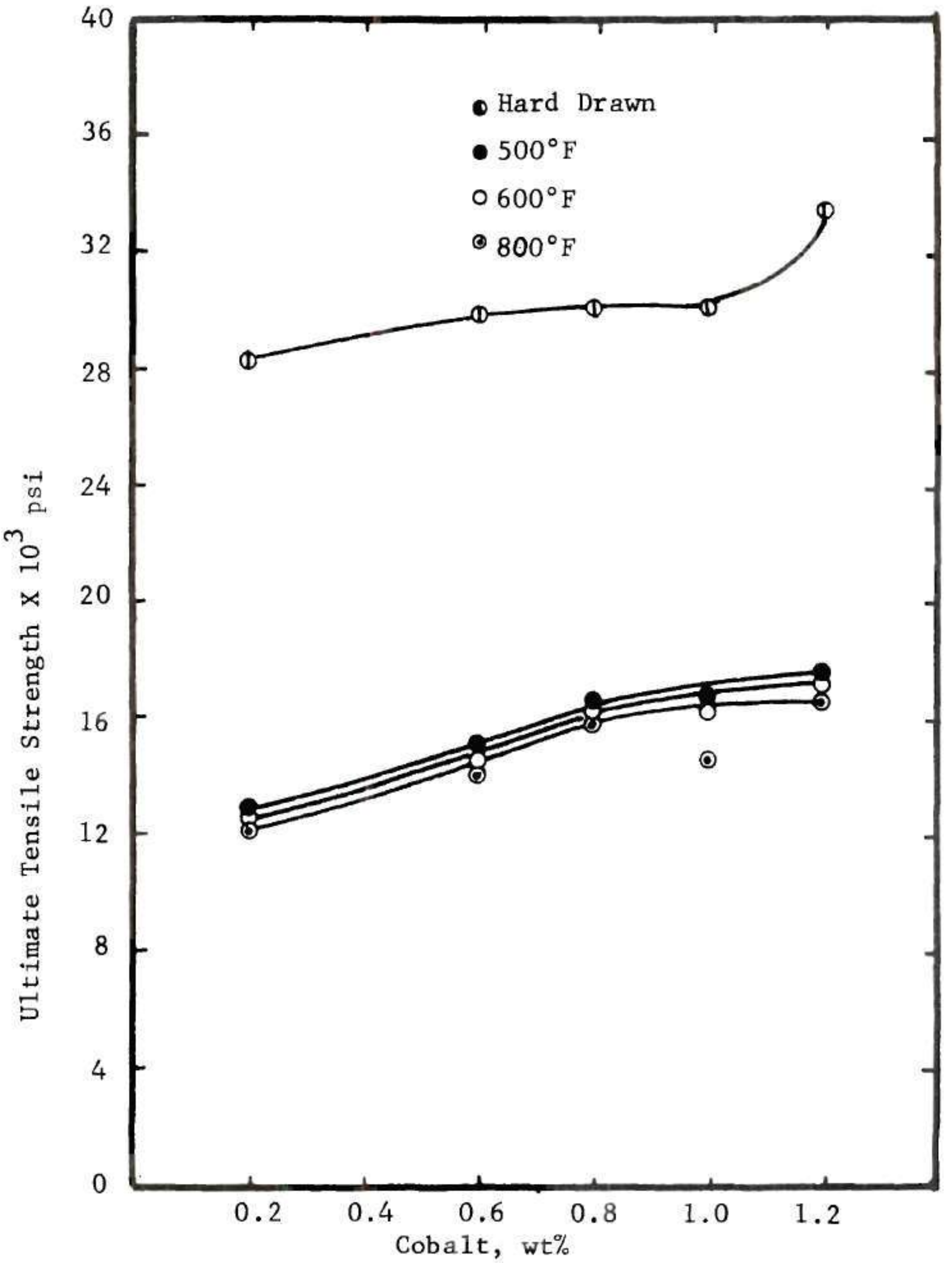


Figure 12. Al-Co Alloys. Effect of Cobalt on the Ultimate Tensile Strength of Aluminum in Hard Drawn and Annealed (500°F 600°F, 800°F) Conditions.

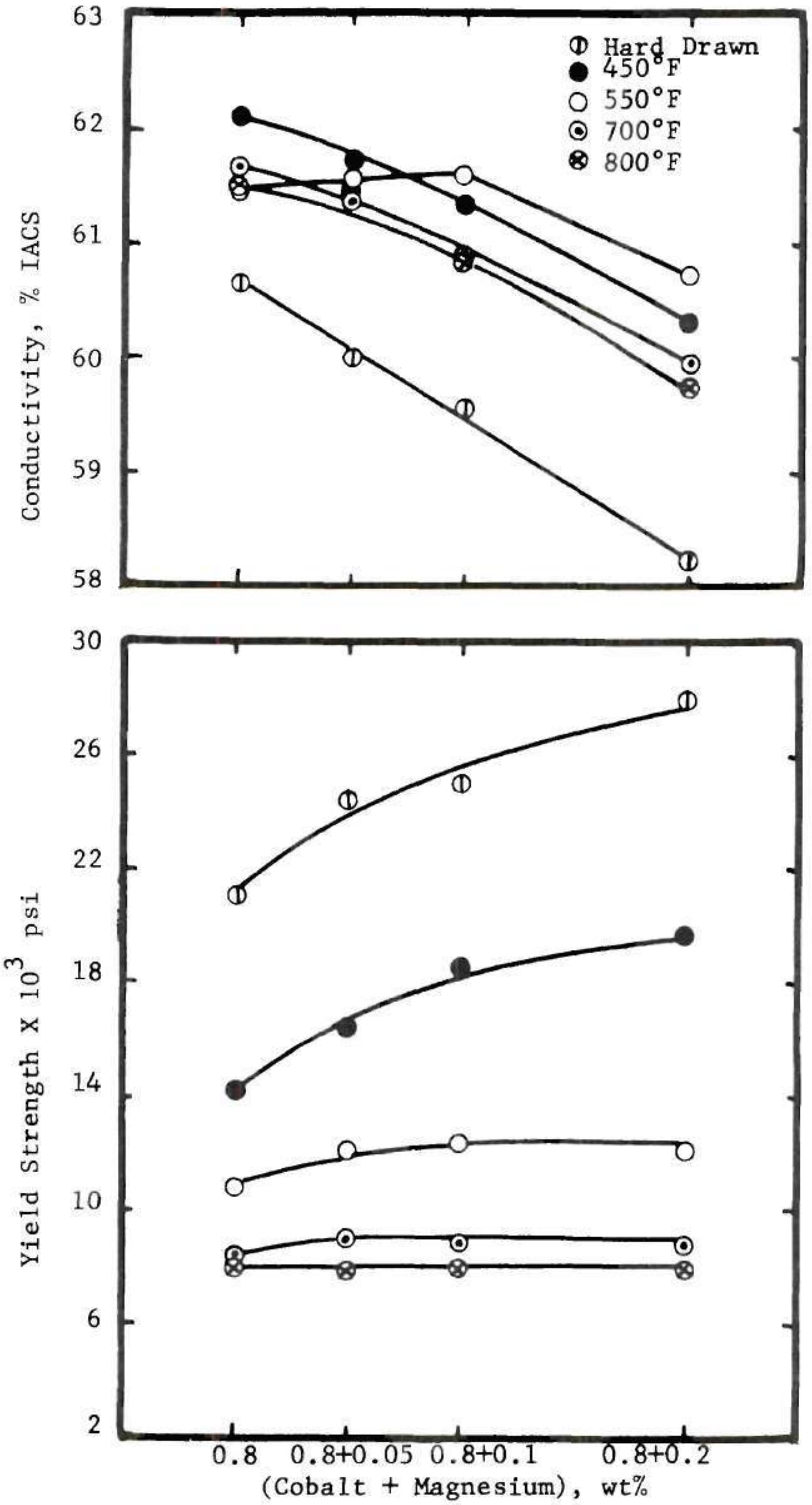


Figure 13. Al-Co-Mg Alloy. Effect of Magnesium Together with Cobalt on the Electrical Conductivity and Yield Strength of Aluminum in Hard Drawn and Annealed (450°F, 550°F, 700°F, 800°F) Conditions.

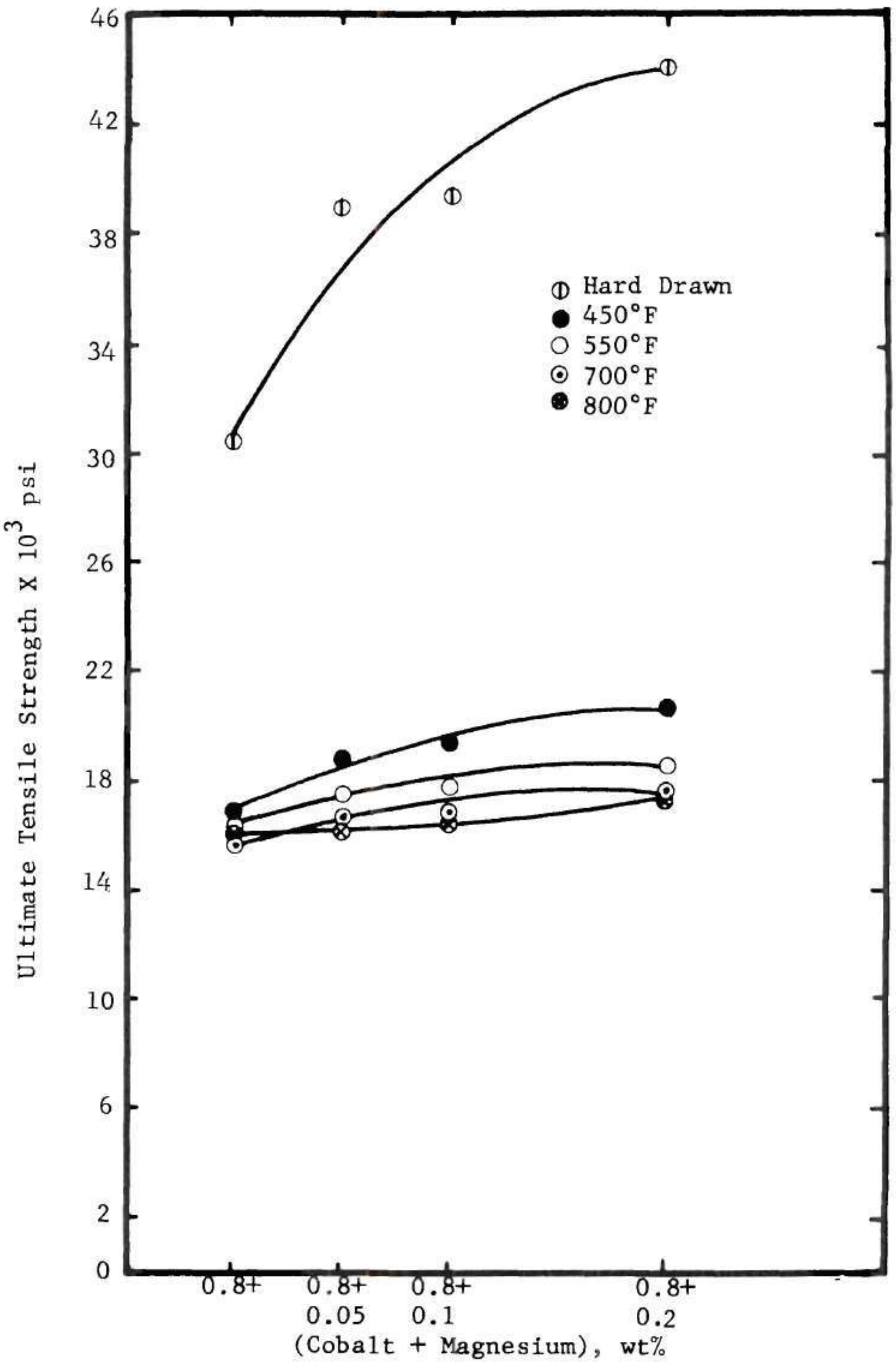


Figure 14. Al-Co-Mg Alloy. Effect of Magnesium Together with Cobalt on the Ultimate Tensile Strength of Aluminum in Hard Drawn and Annealed (450°F, 550°F, 700°F, 800°F) Conditions.

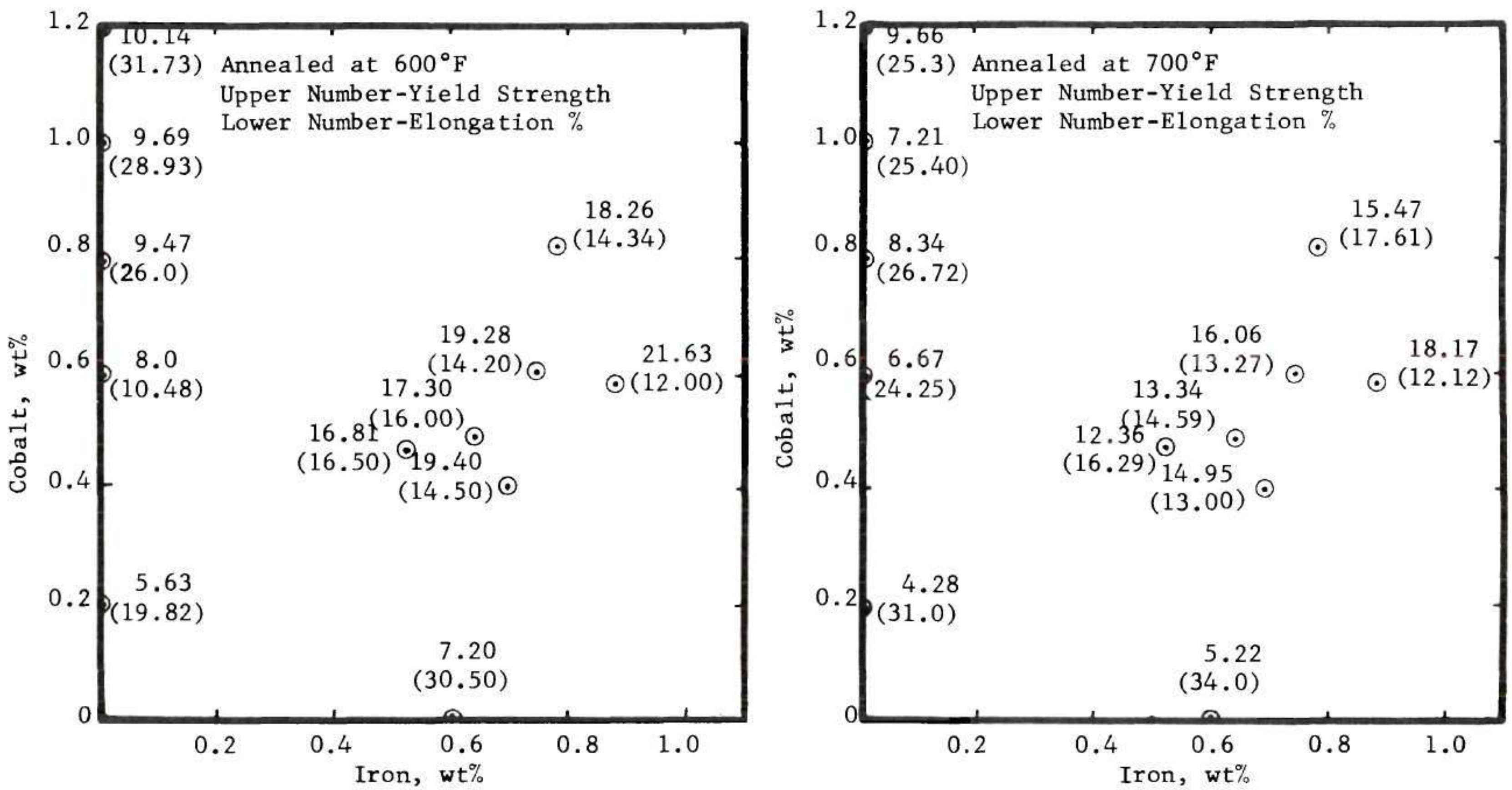


Figure 15. Relative Effect of Fe and Co on the Yield Strength and Elongation of Al-Co-Fe Alloys.

can be improved with higher Fe:Co ratio at the loss of some amount of elongation.

In an effort to compare the properties of the copper, commercial grade pure aluminum and aluminum alloys, the dependency of the mechanical properties and conductivity are plotted against annealing temperature in the Figures 16, 17, 18 and 19. These figures show that an Al-Fe-Co-Mg alloy can be produced with higher yield strength than pure copper, conductor grade aluminum and Al-Co-Mg alloys. The conductivity of the Al-Fe-Co-Mg alloy is about 2% IACS below that of pure aluminum and 39% IACS less than the pure copper in the annealed condition. On the other hand the ultimate tensile strength of the same Al-Fe-Co-Mg alloy is better than commercial grade pure aluminum and Al-Co-Mg alloy when annealed at temperature above 550 F.

In summation, the aluminum alloys with higher mechanical strength than electrical conductor grade (EC) aluminum has been produced. Addition of higher amounts of cobalt and magnesium enhances the mechanical strength but the conductivity is lowered. It is also clear from the present results that with higher Fe:Co ratio, the strength of the Al-Fe-Co-Mg alloy is increased. The conductivity of the aluminum alloys can be improved by annealing at the cost of some strength.

The superior strength properties of Al-Fe, Al-Co, Al-Ni, Al-Co-Mg and Al-Fe-Co-Mg alloys can be attributed to a dispersion strengthening mechanism. The dispersed phase of the intermetallic compound strengthens by obstructing dislocation glide and inhibiting grain growth during recrystallization. The Al-Fe-Co-Mg alloys exhibit the highest strength properties of all the alloys investigated. The strengthening

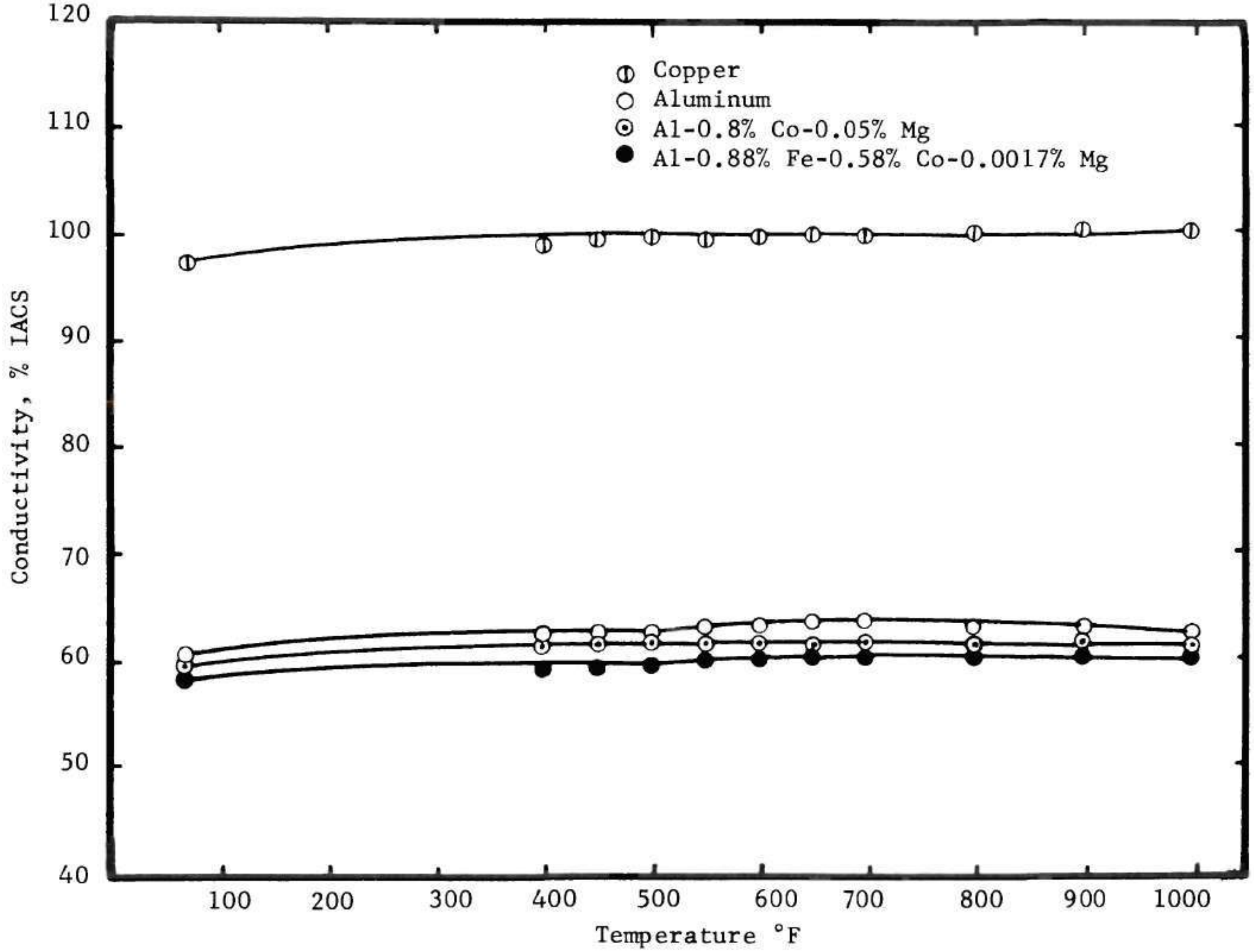


Figure 16. Comparison of Electrical Conductivities of Pure Copper, Aluminum, Al-0.8% Co-0.05% Mg and Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy.

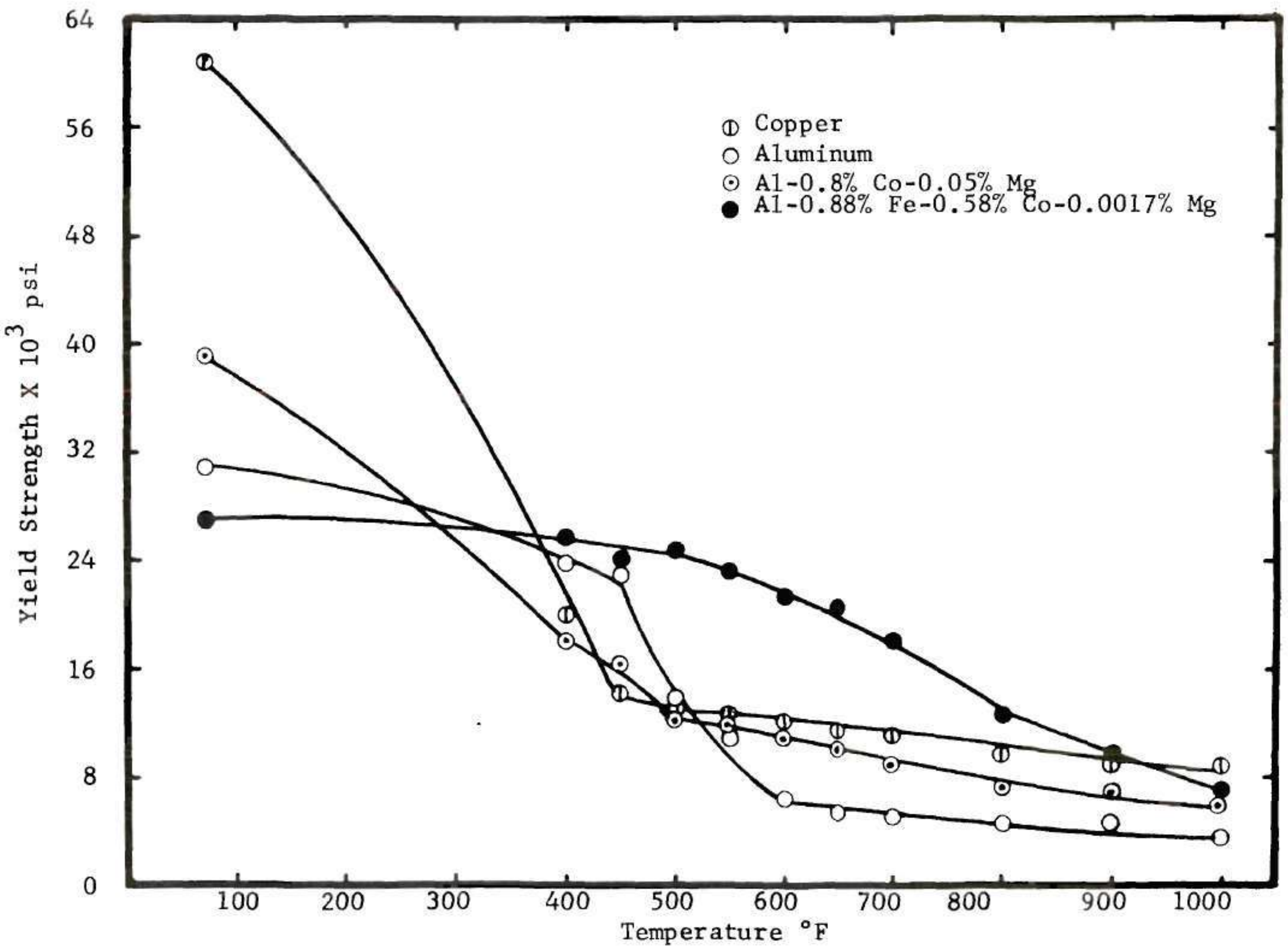


Figure 17. Comparison of Yield Strengths of Pure Copper, Aluminum, Al-0.8% Co-0.05% Mg and Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy.

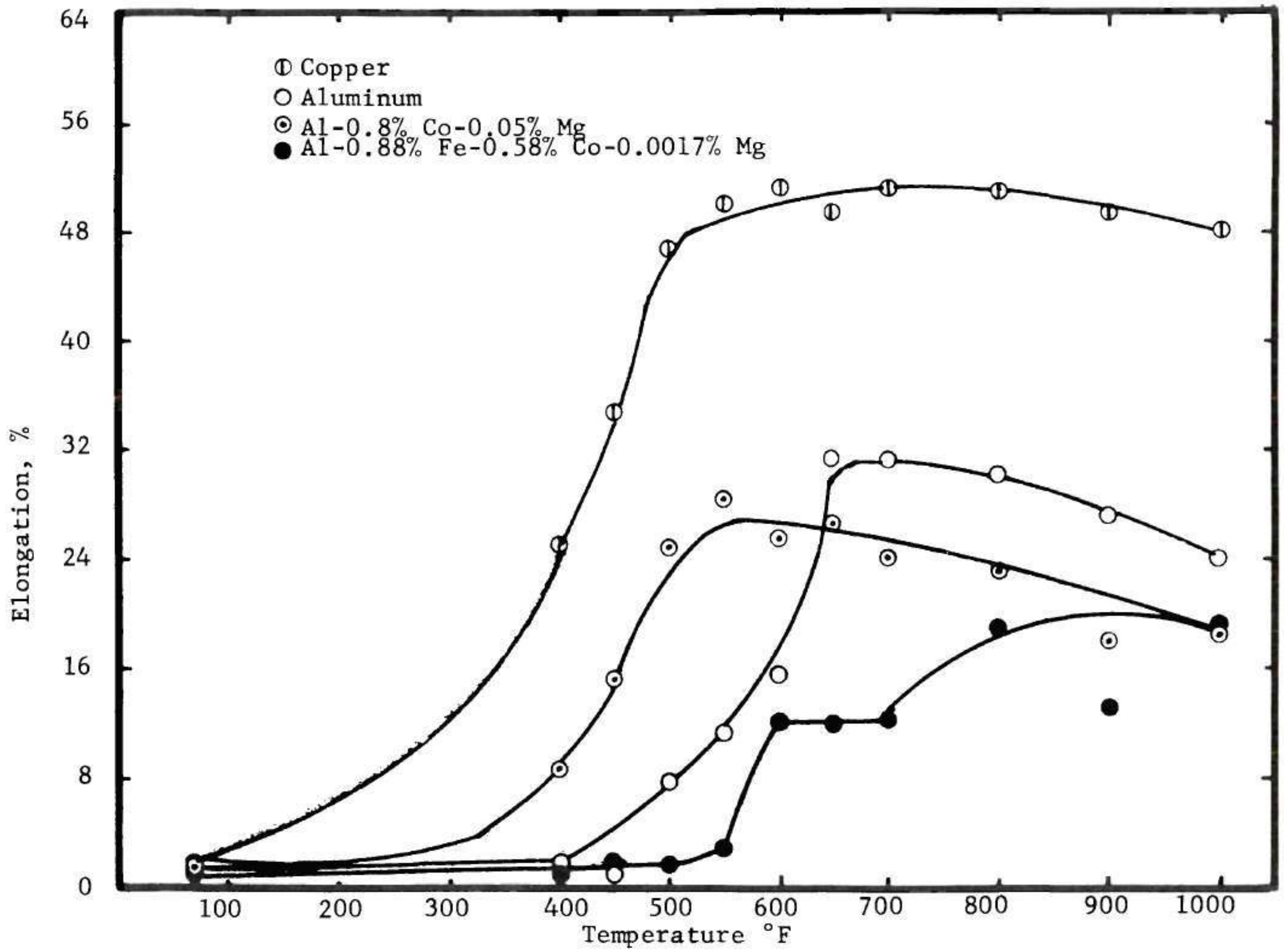


Figure 18. Comparison of Elongations of Pure Copper, Aluminum, Al-0.8% Co-0.05% Mg and Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy.

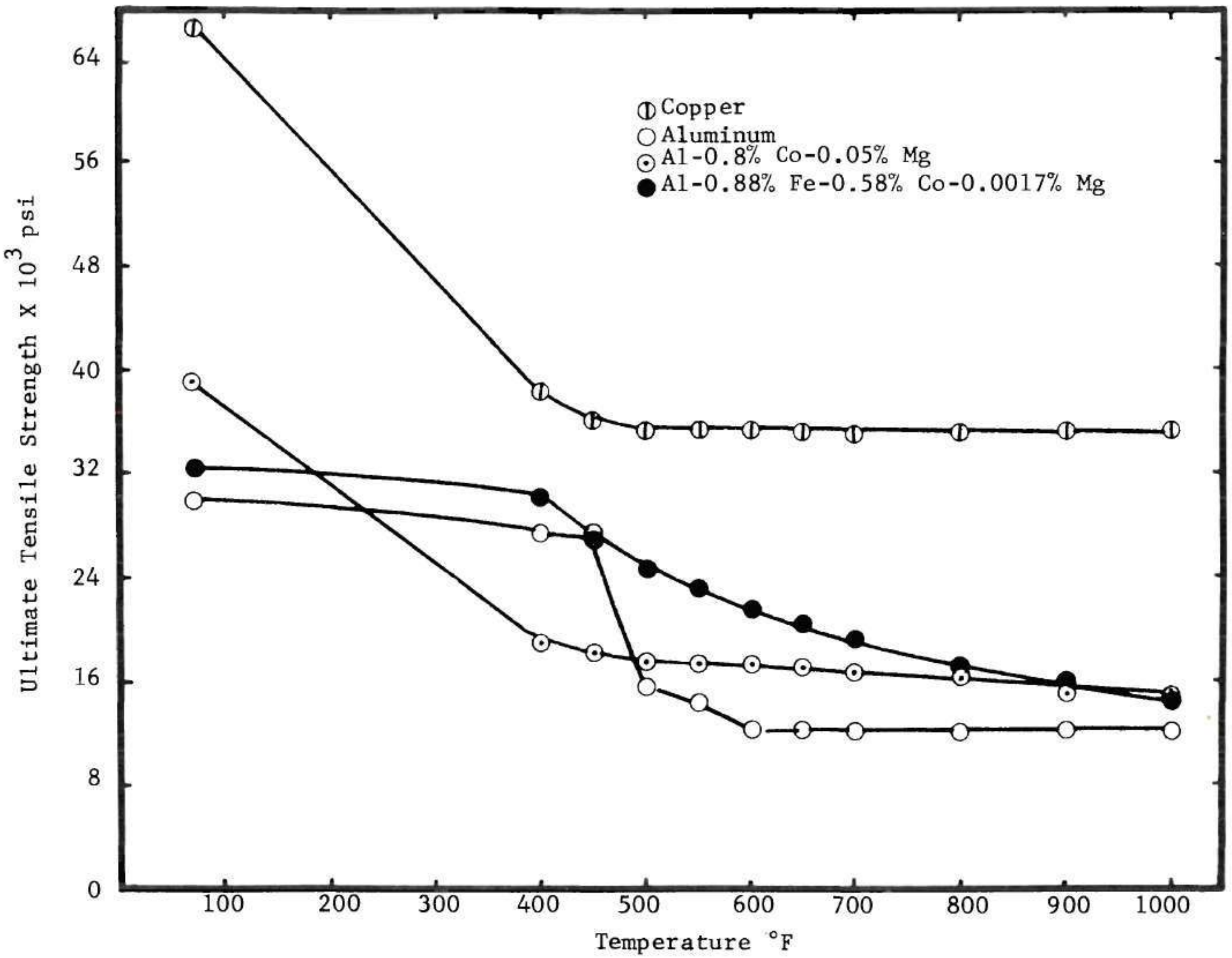


Figure 19. Comparison of Ultimate Tensile Strengths of Pure Copper, Aluminum, Al-0.8% Co-0.05% Mg and Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy.

is mainly due to the Co_2Al_9 precipitates and extremely fine size of the metallic cell or subgrain, the boundaries of which act as a barrier to the dislocation motion. The Co_2Al_9 precipitates have been identified by X-ray analysis and appear (13) as rod or plate shaped aligned in the drawing direction. These rod shaped precipitates form clusters and the breaking down of these clusters might be possible source of the yield point observed in Al-Co alloys containing more than 1.0% Co. Yield phenomena are also observed in alloys containing less than 1.0% Co when Mg is present. The presence of trace amount of magnesium is known (19, 20) to lower the stacking fault energy of aluminum and the magnesium atoms should have a tendency to segregate into the faulted region and obstruct the dislocation glide. Hence the locking of dislocations by magnesium may contribute to the yield point phenomena in Al-Co-Mg and Al-Fe-Co-Mg alloys.

The electrical conductivity of Al-Fe, Al-Co and Al-Ni alloys are slightly better than the magnesium containing alloys. Since the alloying elements Fe, Co and Ni are mostly out of solution, they do not scatter the flow of electrons and hence the conductivity is essentially maintained. But in case of the stronger Al-Co-Mg and Al-Fe-Co-Mg alloys, magnesium remains in solution in small amounts and thereby lowers the electrical conductivity.

CHAPTER V

CONCLUSIONS

1. The fine precipitates of intermetallic compounds (Al_3Fe, Al_3Ni and Co_2Al_9) enhance the yield and tensile strengths of aluminum by inhibiting grain growth and obstructing dislocation glide without much deleterious effect on electrical conductivity.

2. Al-0.78% Fe-0.82% Co-0.006% Mg alloy is found to be the best of all the alloys investigated. When annealed at 600°F, this alloy shows a tensile strength of 19.19×10^3 psi, yield strength 18.26×10^3 psi, elongation 14.35% and conductivity 60% IACS.

3. The recrystallization temperature of Al-Ni alloy (350°F) is lower than the recrystallization temperature of Al-Fe (600°F) and Al-Co (600°F) alloys.

4. Addition of cobalt up to 1.2 percent increases the mechanical properties but the conductivity decreases simultaneously. The best combination of conductivity and mechanical properties is obtained with Al-0.8% Co alloy.

5. Al-Fe-Co-Mg alloy can be produced with better yield strength than pure copper in annealed condition.

CHAPTER VI

SUGGESTIONS FOR FUTURE WORK

1. The Al-Fe-Co-Mg alloys exhibit higher strength properties with increasing Fe:Co ratio; the optimum ratio should be determined.

2. The resistivity of intermetallic compound precipitates should be measured in order to determine the effect of compound precipitates on the conductivity.

3. Since finer dendrite arm spacing increases the mechanical strength of aluminum alloys, further investigation should be carried out on the effect of solidification rate on the structure of ingot.

4. The effect of alloying elements which form stable precipitate should be investigated in order to increase the strength properties.

APPENDIX

Table 2. Electrical Conductivity and Mechanical Properties of 2.17 m.m. Diameter Commercial Grade Pure Aluminum Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	28.00	26.00	0.57	60.48
400	27.79	24.47	1.14	61.58
450	27.72	24.47	1.69	62.05
500	16.90	13.98	7.77	62.70
550	14.51	11.18	11.51	63.26
600	12.23	6.64	15.09	63.13
650	12.23	5.59	31.52	63.72
700	12.06	5.24	31.54	63.49
800	12.06	4.89	30.26	63.49
900	12.06	4.54	27.46	63.37
1000	11.88	3.49	24.00	62.88

Table 3. Electrical Conductivity and Mechanical Properties of 2.04 m.m. Diameter Pure Copper Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS
Hard Drawn	66.56	61.22	1.78	97.64
400	38.31	19.75	25.00	99.25
450	36.34	14.22	35.00	99.81
500	35.55	13.23	47.00	99.81
550	35.55	12.64	50.00	99.81
600	35.55	12.64	51.00	99.87
650	35.55	11.85	49.00	99.87
700	35.15	11.45	50.00	100.00
800	35.15	9.87	50.00	100.00
900	35.15	9.48	49.00	100.00
1000	35.15	9.08	48.00	100.34

Table 4. Electrical Conductivity and Mechanical Properties of 2.71 m.m. Diameter Al-0.3% Mn Alloy Wires Tempered to Indicated Temperature for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	28.55	23.51	1.37	48.20
400	27.99	22.39	1.36	48.87
450	26.53	20.71	1.33	49.54
500	19.93	19.93	2.18	50.09
550	18.14	18.14	2.79	51.18
600	12.98	8.39	13.55	51.90
650	11.75	4.47	27.40	50.75
700	11.64	4.03	28.16	51.09
800	11.87	4.03	33.58	50.87
900	11.87	3.80	38.39	50.52
1000	11.19	3.35	39.00	49.78

Table 5. Electrical Conductivity and Mechanical Properties of 3.20 m.m. Diameter Al-0.6% Fe Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	31.00	30.00	1.34	60.37
400	26.96	25.20	1.58	61.01
450	26.66	25.00	1.70	61.15
500	16.86	15.66	5.85	62.10
550	13.17	7.22	16.51	62.66
600	13.14	7.20	30.50	62.70
650	12.44	5.62	31.65	62.36
700	12.44	5.22	34.07	62.84
800	12.44	4.41	38.20	62.81
900	12.44	4.01	32.02	62.81
1000	12.44	4.01	34.83	62.39

Table 6. Electrical Conductivity and Mechanical Properties of 2.06 m.m. Diameter Al-0.6% Fe Alloy Wires Tempered to Indicated Temperature for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	31.00	29.32	0.58	60.39
400	29.06	27.50	1.14	60.82
450	27.90	25.00	1.16	60.00
500	17.82	17.44	7.10	61.99
550	13.37	8.52	15.93	62.58
600	13.37	8.50	24.00	62.70
650	13.37	7.75	25.42	62.89
700	13.17	5.81	26.66	62.85
800	12.98	5.03	33.14	62.76
900	12.79	4.65	30.14	62.76
1000	12.79	4.26	27.77	62.33

Table 7. Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.6% Fe Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	30.65	25.50	0.58	60.63
400	25.38	23.50	1.14	61.44
450	24.76	22.00	3.46	61.56
500	17.02	15.47	6.58	62.38
550	13.31	7.46	17.90	62.75
600	13.31	6.45	22.00	62.88
650	13.31	4.95	27.95	62.86
700	13.31	4.95	28.57	62.78
800	13.31	4.95	30.00	62.66
900	13.31	4.95	29.58	62.45
1000	13.31	4.95	30.62	62.45

Table 8. Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.8% Ni Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	31.26	26.31	2.22	60.85
300	21.05	18.57	2.0	62.14
350	15.4	13.2	16.0	62.0
400	15.47	11.14	20.40	62.12
450	14.86	8.66	26.00	61.20
500	14.86	7.43	31.31	61.45
550	14.86	6.81	28.00	60.96
600	14.86	6.81	30.00	60.89
650	14.86	6.19	27.66	61.00
700	14.86	5.57	33.67	61.00
800	14.86	5.26	30.38	61.12
900	14.86	4.95	28.00	61.11
1000	10.52	3.09	28.14	61.02

Table 9. Electrical Conductivity and Mechanical Properties of 2.70 m.m. Diameter Al-0.2% Co Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	28.4	24.4	1.35	61.78
400	20.29	20.29	1.25	62.49
450	--	--	--	--
500	12.62	6.20	22.66	63.09
550	12.73	5.86	13.97	62.85
600	12.85	5.63	19.82	62.68
650	12.51	4.50	27.50	62.96
700	12.51	4.28	31.90	62.83
800	12.51	3.94	30.64	62.91
900	11.27	3.88	30.60	62.74

Table 10. Electrical Conductivity and Mechanical Properties of 2.70 m.m. Diameter Al-0.60% Co Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	30.10	25.36	1.89	61.20
400	17.02	15.55	5.30	61.55
450	--	--	--	--
500	14.99	9.01	15.81	61.59
550	14.88	8.56	22.88	61.71
600	14.09	8.00	10.48	61.63
650	14.54	7.55	32.00	61.69
700	14.20	6.67	24.25	61.49
800	13.97	5.97	26.92	61.49
900	13.41	5.07	27.80	61.49

Table 11. Electrical Conductivity and Mechanical Properties of 2.70 m.m. Diameter Al-0.8% Co Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	30.43	25.54	2.23	60.70
400	18.03	16.00	9.45	61.55
450	--	--	--	--
500	16.45	11.27	13.16	61.32
550	16.45	10.82	19.50	61.41
600	16.34	9.47	26.00	61.26
650	16.34	9.25	28.20	61.69
700	15.78	8.34	26.72	61.49
800	16.23	8.34	29.29	61.49
900	14.38	5.97	28.88	61.49

Table 12. Electrical Conductivity and Mechanical Properties of 2.70 m.m. Diameter Al-1.0% Co Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	30.21	26.27	2.48	60.34
400	17.13	14.20	12.60	61.45
450	--	--	--	--
500	16.45	10.93	18.08	61.34
550	16.45	10.93	22.52	61.41
600	16.34	9.69	28.93	61.26
650	16.23	9.69	26.35	61.34
700	15.33	7.21	25.40	61.16
800	14.38	6.98	29.84	61.24
900	14.65	6.31	22.33	61.14

Table 13. Electrical Conductivity and Mechanical Properties of 2.70 m.m. Diameter Al-1.2% Co Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	33.72	33.72	1.34	60.05
400	18.04	15.09	10.61	61.00
450	--	--	--	--
500	17.57	11.43	19.38	61.20
550	17.45	11.20	24.89	61.22
600	17.33	10.14	31.73	61.14
650	17.45	10.37	32.77	61.14
700	17.33	9.66	25.27	61.18
800	16.74	7.78	29.90	61.04
900	16.03	7.07	30.06	61.04

Table 14. Electrical Conductivity and Mechanical Properties of 2.71 m.m. Diameter Al-0.8% Co-0.05% Mg Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	39.19	24.80	1.80	59.93
400	19.02	18.24	8.40	61.16
450	18.35	16.34	15.00	61.71
500	17.57	12.98	25.00	61.59
550	17.57	12.19	28.70	61.69
600	17.45	11.19	25.76	61.63
650	17.23	10.29	27.04	61.41
700	16.78	8.95	24.84	61.45
800	16.00	7.83	23.39	61.47
900	15.66	7.38	18.60	61.34
1000	14.99	6.94	19.04	61.30

Table 15. Electrical Conductivity and Mechanical Properties of 2.71 m.m. Diameter Al-0.8% Co-0.1% Mg Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS
Hard Drawn	39.39	25.00	0.86	59.60
400	21.04	21.04	3.94	61.12
450	19.36	18.69	9.17	61.38
500	17.57	13.65	17.17	61.45
550	17.68	12.31	24.43	61.59
600	17.68	10.18	22.85	61.16
650	17.68	9.73	26.85	61.06
700	16.89	8.95	21.31	60.92
800	16.56	7.83	19.78	60.94
900	15.89	6.71	22.65	60.80
1000	15.33	6.15	22.28	60.80

Table 16. Electrical Conductivity and Mechanical Properties of 2.71 m.m. Diameter Al-0.8% Co-0.2% Mg Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	44.20	40.00	1.20	58.24
400	25.18	22.00	2.64	60.14
450	20.92	19.80	11.90	60.30
475	20.36	19.02	13.90	60.40
500	19.02	15.33	15.90	60.84
525	18.35	12.08	23.60	60.76
550	17.68	11.86	23.60	60.48
600	17.90	11.19	27.00	60.34
700	17.90	8.72	28.00	59.77
800	17.40	7.83	28.60	59.75

Table 17. Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.78% Fe-0.82% Co-0.006% Mg Alloy Wires Tempered to Indicate Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	32.81	30.03	1.80	58.40
400	25.38	22.91	1.11	59.79
450	21.67	22.60	3.53	59.83
500	20.43	20.74	11.11	59.94
550	19.19	18.57	13.36	60.00
600	19.19	18.26	14.35	60.08
650	18.57	16.09	15.87	60.17
700	17.95	15.47	17.61	60.26
800	16.09	11.14	11.34	60.40
900	14.55	8.04	13.00	60.63
1000	13.62	6.19	19.00	60.00

Table 18. Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.74% Fe-0.60% Co-0.0024% Mg Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	32.75	26.52	1.31	59.26
400	30.40	24.90	1.34	60.00
450	25.71	24.90	1.36	60.42
500	22.49	22.49	3.50	60.97
550	21.01	21.01	5.33	60.64
600	20.02	19.28	14.20	60.64
650	20.02	19.03	17.30	60.75
700	18.54	16.06	13.27	60.95
800	16.31	10.50	17.80	61.08
900	14.83	8.03	15.85	61.26
1000	13.84	5.56	21.65	61.34

Table 19. Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.88% Fe-0.58% Co-0.0017% Mg Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	32.60	26.77	1.20	59.16
400	30.16	25.52	1.32	59.57
450	26.82	23.03	1.30	59.94
500	24.72	24.72	1.80	60.10
550	23.34	23.34	3.09	60.26
600	21.63	21.63	12.00	60.05
650	20.76	20.76	11.50	60.37
700	19.40	18.17	12.12	60.48
800	17.30	12.97	19.00	60.64
900	16.19	10.38	13.65	60.86
1000	14.58	7.66	19.64	60.91

Table 20. Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.52% Fe-0.49% Co-0.024% Mg Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	33.99	30.00	0.81	59.42
400	29.91	29.10	0.88	59.94
450	25.46	25.46	1.31	60.64
500	20.76	20.76	8.77	60.75
550	18.78	18.78	12.50	60.91
600	18.78	16.81	16.50	60.75
650	18.78	16.44	19.40	61.02
700	16.93	12.36	16.29	61.12
800	15.45	8.65	23.40	61.19
900	14.46	6.79	17.74	61.30
1000	13.84	4.94	21.30	61.35

Table 21. Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.63% Fe-0.49% Co-0.028% Mg Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	33.37	27.52	0.89	59.26
400	30.03	24.90	1.29	59.89
450	25.58	22.58	1.74	60.42
500	20.75	20.75	4.70	60.64
550	20.02	20.02	9.74	60.69
600	19.03	17.30	16.10	60.48
650	18.91	17.05	13.00	60.86
700	17.05	13.34	14.59	60.91
800	15.69	9.88	22.00	61.02
900	14.70	7.41	18.10	61.19
1000	13.84	5.93	20.85	61.30

Table 22. Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.69% Fe-0.40% Co-0.08% Mg Alloy Wires Tempered to Indicated Temperatures for Three Hours.

Temperature F	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
Hard Drawn	37.08	31.13	0.80	58.59
400	32.75	28.01	1.69	59.21
450	28.43	24.90	1.25	59.68
500	22.86	22.86	3.86	59.94
550	22.00	21.63	9.13	60.15
600	21.13	19.40	14.50	59.94
650	20.88	18.54	15.50	60.15
700	19.15	14.95	13.10	60.37
800	17.18	10.38	18.50	60.37
900	15.94	7.66	16.17	60.53
1000	14.70	5.68	17.16	60.64

Table 23. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of Al-0.6% Fe Alloy Wires Tempered at 500° F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
0.50	24.45	23.50	1.35	61.34
1.0	23.19	22.68	1.90	61.58
1.5	21.31	20.31	1.92	61.72
2.0	17.55	16.09	4.73	61.47
2.5	17.55	15.78	6.28	61.74
3.0	17.55	15.04	4.69	62.31
4.0	16.92	14.73	6.94	62.03
5.0	16.92	14.10	6.92	62.12
6.5	16.61	13.79	7.04	62.12

Table 24. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of Al-0.6% Fe Alloy Wires Tempered at 550°F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
0.50	18.18	16.30	4.50	61.99
1.0	17.24	14.42	5.90	61.76
1.5	15.17	12.07	7.25	62.16
2.0	14.42	9.40	11.98	62.31
3.0	14.42	8.15	14.21	62.51
4.0	14.73	7.52	8.07	62.56
5.0	13.62	9.28	8.69	62.55
6.0	12.38	8.66	11.39	62.53

Table 25. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of Al-0.6% Fe Alloy Wires Tempered at 600°F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
0.50	15.04	10.65	7.83	62.44
1.0	14.42	8.77	12.50	62.51
1.5	13.31	7.43	17.20	62.43
2.0	13.70	6.26	19.09	62.61
2.5	13.00	6.26	16.92	62.26
3.0	13.70	6.26	19.54	62.72
4.0	13.47	6.26	17.00	62.37
5.0	13.47	6.26	21.62	62.67
6.0	13.47	6.26	22.42	62.70

Table 26. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of Al-0.6% Fe Alloy Wires Tempered at 700°F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
0.25	13.80	8.04	15.22	62.06
0.50	13. 79	6.81	18.75	62.06
1.0	13.79	6.26	25.00	62.71
2.0	13.79	5.64	19.44	62.80
3.0	13.79	5.64	25.47	62.77
4.0	13.47	5.32	26.41	62.87
5.0	13.0	5.57	24.21	62.44
6.0	13.0	5.26	27.17	62.55

Table 27. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.8% Ni Alloy Wires Tempered at 400°F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	15.78	12.38	20.44	61.54
2	15.47	11.76	20.99	61.68
3	15.47	11.14	20.90	61.55
4	15.17	10.83	26.90	61.61
5	14.86	10.52	26.70	61.53
6	14.86	10.52	29.94	61.52

Table 28. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.8% Ni Alloy Wires Tempered at 500°F.

Time (Hr.)	Ultimate Tensile Strength x 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	14.86	8.66	30.00	61.51
2	14.86	8.04	31.38	61.45
3	14.86	7.43	31.31	61.45
4	14.86	7.43	34.44	61.45
5	14.86	7.12	29.83	61.39
6	14.86	6.81	34.44	61.34

Table 29. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 1.63 m.m. Diameter Al-0.8% Ni Alloy Wires Tempered at 600°F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	15.17	6.81	32.00	61.11
2	15.17	6.81	31.55	61.17
3	14.86	6.81	30.00	61.17
4	14.86	6.19	27.27	61.16
5	14.86	6.19	27.16	61.15
6	14.86	6.19	31.50	61.12

Table 30. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.60% Co-0.74% Fe-0.0024% Mg Alloy Wires Tempered at 400 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1.0	31.39	31.39	0.869	59.57
2.0	29.66	29.66	0.869	59.73
3.0	29.17	29.17	0.881	59.80
4.0	29.04	29.04	0.869	60.03
6.0	26.82	26.82	0.870	60.00

Table 31. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.6% Co-0.74% Fe-0.0024% MgAlloy Wires Tempered at 500 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	22.12	22.12	3.5	60.58
2	22.12	22.12	3.05	60.58
3	22.24	22.24	2.17	60.60
4	22.24	22.24	2.21	60.60
5	21.50	21.50	5.19	60.60
7	21.50	21.50	5.62	60.73

Table 32. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.74% Fe-0.6% Co-0.0024% Mg Alloy Wires Tempered at 600 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	19.77	19.03	11.11	60.66
2	19.65	18.78	11.73	60.78
3	19.77	19.03	14.28	60.88
4	19.77	19.03	14.20	60.89
5	18.54	16.44	14.09	61.17

Table 33. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.58% Co-0.88% Fe-0.0017% Mg Alloy Wires Tempered at 400 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1.0	30.53	30.53	0.877	59.42
2.0	29.66	29.66	0.873	59.42
3.0	28.43	28.43	0.870	59.56
4.0	26.94	26.94	0.865	59.64
6.0	26.94	26.94	0.865	59.64

Table 34. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.58% Co-0.88% Fe-0.0017% Mg Alloy Wires Tempered at 500 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	24.35	24.35	1.70	60.03
2	23.73	23.73	1.76	60.19
3	23.73	23.73	1.32	60.10
4	23.73	23.73	1.76	60.14
5	23.48	23.48	1.74	60.12
7	23.48	23.48	2.20	60.28

Table 35. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.58% Co.-0.88% Fe-0.0017% Mg Alloy Wires Tempered at 600 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	21.01	20.76	9.29	60.30
2	20.64	20.27	10.36	60.48
3	20.70	20.27	10.49	60.48
4	20.64	20.27	10.04	60.48
5	20.64	20.27	8.29	60.37

Table 36. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% Co-0.52% Fe-0.024% Mg Alloy Wires Tempered at 400 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1.0	30.90	30.90	0.873	59.61
2.0	29.41	29.41	0.881	60.05
3.0	29.29	29.29	1.09	60.17
4.0	27.81	27.81	0.865	60.10
6.0	26.57	26.57	0.870	60.07

Table 37. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% Co-0.52% Fe-0.024% Mg Alloy Wires Tempered at 500 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	20.14	20.14	7.92	60.77
2	20.27	20.27	7.48	60.82
3	20.02	19.65	6.22	60.71
4	20.14	19.77	10.50	60.82
5	19.90	19.53	9.60	60.80
7	20.27	20.02	9.91	60.98

Table 38. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% Co-0.52% Fe-0.024% Mg Alloy Wires Tempered at 600 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	18.54	16.81	12.82	60.89
2	18.17	15.82	13.97	61.15
3	18.17	16.30	13.45	61.17
4	18.54	16.30	13.15	61.13
5	18.66	16.81	11.25	61.06

Table 39. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% Co-0.63% Fe-0.028% Mg Alloy Wires Tempered at 400 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1.0	30.90	30.90	0.843	59.54
2.0	29.91	29.91	0.860	59.82
3.0	30.28	30.28	1.31	59.91
4.0	28.43	28.43	0.869	59.89
6.0	28.43	28.43	0.873	60.89

Table 40. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% CO-0.63% Fe-0.028% Mg Alloy Wires Tempered at 500 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	21.01	21.01	4.38	60.71
2	21.26	21.26	3.96	60.58
3	20.51	20.51	6.98	60.55
4	20.88	20.88	6.11	60.66
5	20.64	20.64	7.79	60.55
7	20.64	20.64	7.42	60.69

Table 41. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.49% Co-0.63% Fe-0.028% Mg Alloy Wires Tempered at 600 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	18.66	17.30	13.53	60.75
2	18.66	16.81	14.02	60.86
3	18.66	17.30	13.21	60.93
4	18.78	16.93	12.39	60.91
5	18.78	17.18	10.96	60.89

Table 42. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.40% Co-0.69% Fe-0.08% Mg Alloy Wires Tempered at 400 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1.0	34.61	34.61	0.877	58.97
2.0	32.88	32.88	0.877	58.99
3.0	32.38	32.38	0.881	59.17
4.0	30.90	30.90	0.869	59.16
6.0	29.66	29.66	0.877	59.00

Table 43. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.40% Co-0.69% Fe-0.08% Mg Alloy Wires Tempered at 500 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	23.11	23.11	3.96	60.00
2	23.23	23.23	3.47	59.98
3	23.11	23.11	3.96	59.75
4	22.99	22.99	6.98	59.96
5	22.62	22.62	7.48	59.92
7	22.24	22.24	8.58	60.14

Table 44. Influence of Heat Treatment Time on the Electrical Conductivity and Mechanical Properties of 2.57 m.m. Diameter Al-0.40% Co-0.69% Fe-0.08% Mg Alloy Wires Tempered at 600 F.

Time (Hr.)	Ultimate Tensile Strength X 10^3 p.s.i.	Yield Strength X 10^3 p.s.i.	Elongation Percentage	Conductivity % IACS.
1	20.88	19.53	12.17	60.00
2	21.26	19.53	12.30	59.96
3	20.84	19.53	13.21	60.24
4	21.01	19.03	12.28	60.24
5	20.88	18.54	9.69	60.19

BIBLIOGRAPHY

1. F. R. Collins, A. G. Craig and H. Y. Hunsicker, Wire Journal, October, 1970, p. 142.

2. S. C. Rao and A. C. Biswas, Traction Installation Directorate Research Designs and Standard Organization, Lucknow, India, 1970.

3. I. S. Hirschhorn, Journal of Metals, October, 1970, p. 40.

4. George E. Lenaeus, Wire Journal, September, 1970, p. 66.

5. Ya B. Kruoptkin and M. B. Gokhshtein, Tsventnyye Metally, Vol.38, No. 5, 1965.

6. R. H. Harrington, Transactions A.S.M., Vol. 41, 1949.

7. G. J. Herbert, K. M. Olsen and T. D. Schlabach, Wire Journal, August, 1970.

8. H. Chia and E. A. Starke, Paper Presented at the Combined Meeting of Non-ferrous and Electrical Divisions of the Wire Association in Dallas, Texas, March 29, 1971.

9. Aluminum, Vol. 1, Edited by K. R. Van Horn, A. S. M., Metals Park, Ohio, 1967.

10. D. Altenpohl and D. Velze, Metals and Materials, February, 1971, p. 65.

11. Niels N. Engel, Metals and Alloys as Electron Concentration Phases, Course guide for Met. 741, Georgia Institute of Technology, 1967.

12. Ya M. Krupotkin and S. M. Borts, Metallovedenie i tercheskaya Obrabotka Metallov, No. 8, p. 43-45, August, 1969.

13. Southwire Research Report, 1970.

14. G. G. Gauthier, Journal of Institute of Metals, Vol. 59, 1936.

15. D. B. Cofer, Wire and Wire Products, December, 1963.

16. M. Hansen, Constitution of Binary Alloys, McGraw Hill, New York, 1965.

17. Elliott, Constitution of Binary Alloys, McGraw Hill, New York, 1965.

18. T. F. Bower, S. N. Singh and M. C. Flemings, Metallurgical Transactions, Vol. 1, No. 1, January, 1970, p. 191.

19. James G. Morris, Technical Report AFML-TR-68-339, November, 1968.

20. E. O. Hall, Yield Point Phenomena in Metals and Alloys, Plenum Press, New York, 1970.